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# Gold and Other Minor Elements Associated with the Hot Springs and Geysers of Yellowstone National Park, Wyoming, Supplemented with Data from Steamboat Springs, Nevada

By DONALD E. WHITE, CHRIS HEROPOULOS, and
R.O. FOURNIER

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# Gold and Other Minor Elements Associated with the Hot Springs and Geysers of Yellowstone National Park, Wyoming, Supplemented with Data from Steamboat Springs, Nevada

*By* Donald E. White, Chris Heropoulos, *and* R.O. Fournier

**Abstract**

A commonly held theory of the origin of epithermal ore deposits relates Au, Ag, Hg, As, Sb, Tl, and other "volatile" elements to "fossil" hot-spring systems that transported and deposited these metallic elements close to the ground surface existing at the time. In the early 1970's, an emission-spectrographic method using short-wavelength radiation (SWR) was developed for use in the analysis of these "volatile" elements. This method was applied to 125 samples of rock and hot-spring chemical precipitates from Yellowstone National Park and 43 samples from Steamboat Springs, Nev. The results of those analyses are presented here. Recently, other, more sensitive methods for the analyses of gold and volatile elements have been developed and (or) become less expensive, but these methods generally have not yet been applied to Yellowstone samples.

A few samples from Yellowstone National Park and Steamboat Springs were analyzed by neutron-activation (NA) and SWR methods, as well as by fire assay. In general, the results from the SWR method agree more closely with those from the fire-assay than the NA method. Present findings reveal significant gold contents (more than 0.1 ppm) in only a few samples from Yellowstone, but the general principles relating Yellowstone's hot-spring and geyser activity to gold transport and deposition are of considerable interest as a guide to how gold deposits may have formed elsewhere.

Concentrations of Sb, As, Hg, B, Tl, and Zn vary widely with respect to Au and each other in the Yellowstone and Steamboat Springs samples. Although Au appears to be concentrated in samples rich in Sb and As, high Sb or As contents do not necessarily require correspondingly high Au contents. Tl is 10 to 100 times lower in abundance in Yellowstone samples than in Steamboat Springs samples. At Yellowstone, however, the best correlation of Au with SWR-analyzed metallic elements appears to be with Tl.

The distribution of gold in Yellowstone National Park is more restricted than at Steamboat Springs, possibly because of greater dilution by a more abundant water supply at Yellowstone.

Manuscript approved for publication, June 18, 1991.

## INTRODUCTION

A commonly held theory of the origin of epithermal ore deposits relates Au, Ag, Hg, As, Sb, and other "volatile" elements to "fossil" hot-spring systems that transported and deposited these metallic elements close to the ground surface existing at the time. A second group of epithermal deposits, consisting mainly of the base metals Cu, Pb, Zn, and Ag, is generally thought to form at greater depth within hydrothermal systems. Base-metal deposits are not considered in this report, although zinc is reported here as a trace element. Silver is commonly present in both groups and generally becomes more abundant downward where the base metals underlie "volatile element" deposits.

Geologists and geochemists familiar with low-grade, dispersed, epithermal gold deposits have applied various names to them, including "bulk minable," "sediment hosted," and "invisible gold." These types of deposits became the focus of exploration programs in the 1960's, when the value of gold increased dramatically. Gold is now routinely analyzed at levels above 1 part per billion (ppb) by neutron-activation (NA), and of 1–2 ppb by inductively coupled plasma atomic-emission spectroscopic (ICP–AES), methods. In the 1960's and 1970's, however, these analytical techniques were either very expensive (NA method) or unavailable (ICP–AES method), and so the small gold concentrations in dispersed deposits were seldom detected by the then-prevalent standard analytical methods (fire assay and spectrographic). Therefore, a group of associated trace elements, generally more abundant and more widely distributed than Au, including Ag, Hg, As, Sb, and Tl, became useful indicators that provide broader targets more easily identifiable than Au alone.

In the early 1970's, a short-wavelength-radiation (SWR) emission-spectrographic method was developed by one of us (C.H.) and applied to the analysis of those "volatile" elements that are transported under conditions similar to those for gold. This method is as much as 100 times more sensitive than conventional spectrographic methods. Typical detection limits for conventional spectrographic analyses have been lowered by the SWR method, respectively, from 7 to 0.1 ppm for Au, from 700 to 1.0 ppm for As, and from 300 to 3 ppm for Sb. The only element closely associated with Au that is not determined more reliably by the SWR method than by conventional spectrographic methods is Ag; detection limits for Se, Te, and Bi are also improved.

Analytical data were compiled over a time period of about 15 years. Steamboat Springs, Nev., is well known for its current deposition of Au, Ag, Hg, and Sb, but little has been published about the distribution of these elements within the Yellowstone National Park hydrothermal system. Although present findings reveal significant gold concentrations (more than 0.1 ppm) in only a few Yellowstone samples, the general principles relating Yellowstone's hot-spring and geyser activity to gold transport and deposition are of great interest as a guide to how gold deposits may have formed elsewhere. We realize that many advances have been made in techniques for the rapid analysis of trace amounts of gold and related elements since our cooperative effort started in the early 1970's, but our results for the broad suite of volatile elements found in the hot-spring deposits at Yellowstone National Park and Steamboat Springs are still of interest because the data have generally not been superseded by newer analyses.

The background Au contents of fresh volcanic rocks of Yellowstone National Park were carefully studied in two related reports by Gottfried and others (1972) and Tilling and others (1973), utilizing NA analysis in combination with fire assay for radiochemical separation. The Au contents of most of Yellowstone's fresh rocks range from 0.1 to 60 ppb and average 0.5 ppb; the Au contents of Yellowstone's thermal waters range from less than 0.004 to 0.1 ppb and average about 0.004 ppb (all much too low for the SWR method).

We make no effort to duplicate in this report the careful background study of the gold contents of fresh rocks or of water, as determined by Gottfried and others (1972) and Tilling and others (1973). Instead, we concentrate on determining the gold contents of precipitates and hydrothermally altered rocks within the above-described analytical limits of the SWR method.

The locations of sampled thermal areas in Yellowstone National Park, mainly within the caldera, are shown in figure 1. The locations of Steamboat Springs samples were adequately described in previous publications (Brannock and others, 1948; White, 1968), except that analytical data on samples from drill holes GS–2, GS–5, and GS–6 are also reported here.

*Acknowledgments.*—We are grateful to the National Park Service for allowing samples to be collected from hot springs and for the opportunity provided for research drilling in the park. The continuing cooperative efforts of R.A. Hutchinson, National Park Service geologist, are especially appreciated. In addition to many other activities, he helped in collecting samples from Dantes Spring of the Sylvan Group of western Gibbon Geyser Basin, and from Beryl Spring in Gibbon Canyon.

## COMPARISON OF ANALYTICAL METHODS FOR GOLD

A few samples from Steamboat Springs and Yellowstone National Park were analyzed by NA and SWR methods, as well as by fire assay (table 1). Au contents below 0.1 ppm are reported by the SWR method as <0.1 (later analyses) or <0.2 ppm (earlier analyses). Only a few samples of the material analyzed by different methods were collected at the same time and place; most samples were from common localities but were collected on different dates.

In general, the results from the SWR method agree more closely with those from the fire-assay than the NA method. The NA results for two samples from Steamboat Springs (W–50 and W–91) are considerably higher than those obtained by the other two methods. In contrast, NA gives much lower values than the other two methods for the samples from Beryl Spring in Yellowstone National Park (fig. 1). However, the samples from Beryl Spring that were analyzed by the NA method were collected at a different date and place than the samples analyzed by the SWR and fire-assay methods.

## DIAGENESIS OF THE HYDROTHERMAL SILICA MINERALS

Because of the close affinity of gold with silica in the veins of many deposits, the diagenesis of hydrothermal silica is considered here before the metallic-element analyses are discussed. By definition, sinter (normally, amorphous opal) forms by direct chemical precipitation of $SiO_2$ from hot water discharging at the surface. As the hot water cools, the solubility of $SiO_2$ decreases, and the solution becomes supersaturated, first with respect to quartz and then to more soluble silica species (fig. 2). The rates of polymerization of dissolved silica and growth of crystalline silica phases decrease drastically as the temperature declines (White and others, 1956; Fournier, 1973, 1985; Rimstidt and Barnes, 1980). Hot waters rising to the ground surface commonly have dissolved $SiO_2$ contents that exceed the solubility of amorphous silica. A water-rich amorphous product commonly precipitates, forming either hard sinter (if cooled and dried rapidly, such as near a geyser vent) or silica gel (which may harden over time if subjected to wetting and drying). All or most of the samples listed in table 2 consist predominantly of amorphous opal.

Opaline sinter commonly becomes buried under additional sinter and other sedimentary deposits. In an active high-temperature system where temperatures are generally on or near a reference boiling curve (see White and others, 1975, fig. 24), buried opal undergoes diagenetic changes with increasing time and depth of burial, first crystallizing to cristobalite and eventually to chalcedony or quartz. In addition to the transformation of opaline sinter to chalcedony, other chalcedony is deposited underground from solution within porous cavities in sinter. As much as 50 percent of the chalcedony in a dense chalcedonic sinter probably formed by direct deposition

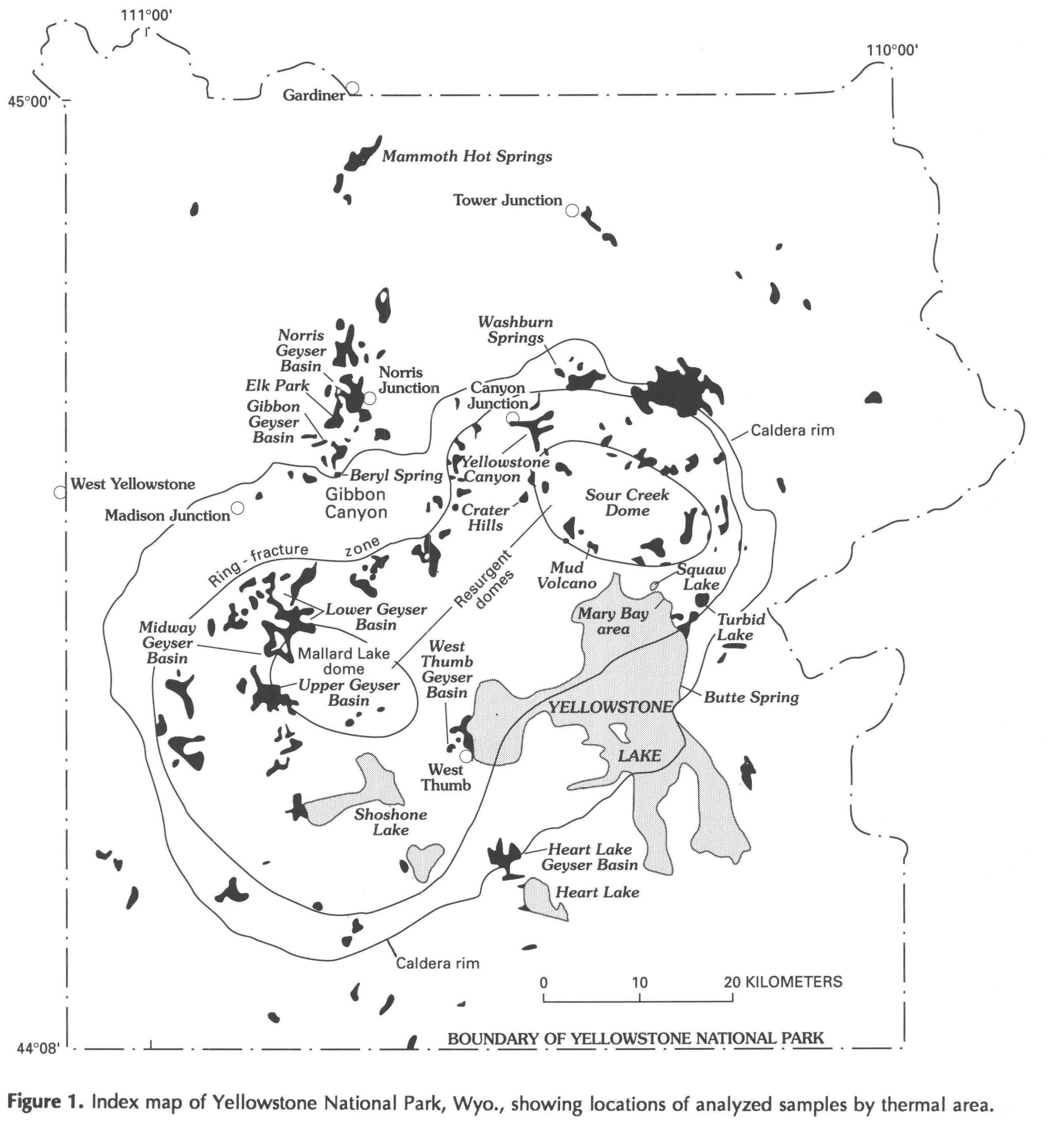


**Figure 1.** Index map of Yellowstone National Park, Wyo., showing locations of analyzed samples by thermal area.

**Table 1.** Reported Au contents in some hot-spring deposits of Yellowstone National Park, Wyoming, and Steamboat Springs, Nevada

[All analyses in parts per million. Neutron-activation (NA) analyses by J.J. Rowe, short-wavelength-radiation (SWR) emission-spectrographic analyses by C. Heropoulos, and fire-assay analyses by W.I. Smyth (University of Nevada, School of Mines). Sp., spring]

| | NA | SWR | Fire assay |
|---|---|---|---|
| **Yellowstone National Park, Wyoming** | | | |
| Old Faithful Sinter, Upper Basin | 0.0053 | — | — |
| Daisey Green, Upper Basin | .0024 | — | — |
| Travertine, Hillside, Upper Basin: | | | |
| Outside | .0102 | — | — |
| Inside | .0045 | <.1 | — |
| Dantes sinter, Sylvan, Gibbon Basin | .813, 0.857 | .66 | .58 |
| Beryl Spring, Gibbon Canyon | .538, 0.593 | 10 | 3 |
| Porkchop Geyser, Norris Basin | .078 | — | — |
| Echinus Geyser, Norris Basin | .075 | — | — |
| Marcasite-pyrite veinlet | — | .74 | — |
| Pyrite-marcasite veinlet | — | <.1 | — |
| Steamboat Geyser, Norris Basin: | | | |
| Pyrite coating on erupted cobble | 9.29 | .74 | — |
| **Steamboat Springs, Nevada** | | | |
| W–37eh, Sp. 24, 5/29/45, dark mud | 7.8 | — | — |
| W–50, Sp. 24, 6/21/45, dark mud | 200 | 15 | 10.0 |
| W–88, Sp. 21, 9/28/45, light mud | .278 | .2 | .14 |
| W–91, Sp. 27, 11/1/45, dark mud | 23.7 | .5 | .56 |
| W–128–8, chalcedonic sinter | .050 | — | — |
| W–128–9, Sp. 23, spouter, opal, calcite | .280 | — | — |
| W–128–10, calcite deposited in erupting Steamboat well, 1949. | .0026 | — | — |
| W–226, fragmental sinter | .0136 | — | — |

from cooling hydrothermal waters. In a final stage, when the flow rate is very slow and the degree of silica supersaturation in the upflowing water has greatly diminished, well-formed quartz crystals deposit as linings that coat the last of the open spaces.

Silica-saturated water also may deposit chalcedony in subsurface channels or veins. Some chalcedonic sinter resembles subsurface vein chalcedony, except that the veins commonly crosscut relict bedding of sinter. The veins generally are deposited along steeply dipping fractures, with deposition progressing inward as the veins grow; mirror images form on the vein walls, with the central part commonly being the last to form. True chalcedonic sinter commonly contains crosscutting veinlets that are the feeder channels for upflowing chalcedonizing solutions. Thus, chalcedonic sinters are complex in origin, partly formed by reconstitution of original opaline sinter and partly by direct deposition of chalcedony from rising $SiO_2$-rich water.

The early history of vein chalcedony and cristobalite is commonly uncertain. Some chalcedony and cristobalite may show relict shrinkage cracks and banding that indicate replacement of an original, more water rich form, probably gelatinous silica or opal.

## GOLD AND ASSOCIATED ELEMENTS DEPOSITED FROM HOT-SPRING SYSTEMS AT YELLOWSTONE NATIONAL PARK

Hydrothermal activity in Yellowstone National Park may have started during or soon after collapse of the large third-stage Yellowstone caldera about 600 ka, which accompanied the eruption of major ash flows. Huge rhyolite lava flows were erupted during the past 200 ka, especially in the western part of the caldera (Christiansen, 1984), concealing evidence of any early postcaldera hydrothermal activity that may have occurred within the caldera. Circulating meteoric water is so abundant and heat supply is so great (Fournier and others, 1976; Fournier, 1989) that geysers and former geysers are a major part of the thermal discharge. Possibly because of the abundant meteoric-water supply, the thermal liquids contain only about 30 percent as much dissolved solids as those of Steamboat Springs. Yellowstone's very dilute near-surface waters may help to explain why the evidence for abundant transport and deposition of gold and related elements is relatively weak.

## Opaline Hot-Spring Sinter

The Au contents of most samples of opaline hot-spring sinter (table 2) were below the limit of detection by the SWR method (0.2 ppm, later lowered to 0.1 ppm). A few samples of amorphous silica collected by Fournier in 1962 were submitted for NA analysis with other samples from Steamboat Springs obtained by White (table 1). All samples contained detectable gold at the parts-per-billion level.

Beryl Spring in Gibbon Canyon, about 1 mi south of Gibbon Geyser Basin, is one of the few springs in Yellowstone National Park that is depositing sinter with gold in the range 0.5–10 ppm. This spring was described by Allen and Day (1935, p. 332) as having a beautiful pool, about 6 m in diameter and 91°C in temperature, and a nearby superheated fumarole (96.3°C, when its boiling temperature should have been limited to about 92.8°C). Samples of sinter from Beryl Spring collected in 1962 contained 0.538 and 0.593 ppm Au in duplicate NA analyses (table 1). Of four samples from Beryl Spring collected by D.E. White and R.A. Hutchinson in 1984 (84–7 through 84–9a, table 2), one sample contained less than 0.1 ppm Au, and the other three from 3 to 10 ppm Au.

Sylvan Springs in the southwestern part of Gibbon Geyser Basin (Allen and Day, 1935, p. 400–403) had little significant discharge at the time of Allen and Day's study, and no detailed map of the Sylvan Group was then available. Allen and Day mentioned only one spring of the group by name, called "Evening Primrose"; its temperature was 64°C. No other spring had a temperature above 87.8°C when these early observations were made.

Dantes Inferno in the Sylvan Springs area came into existence in 1959 at or near the time of the Hebgen Lake

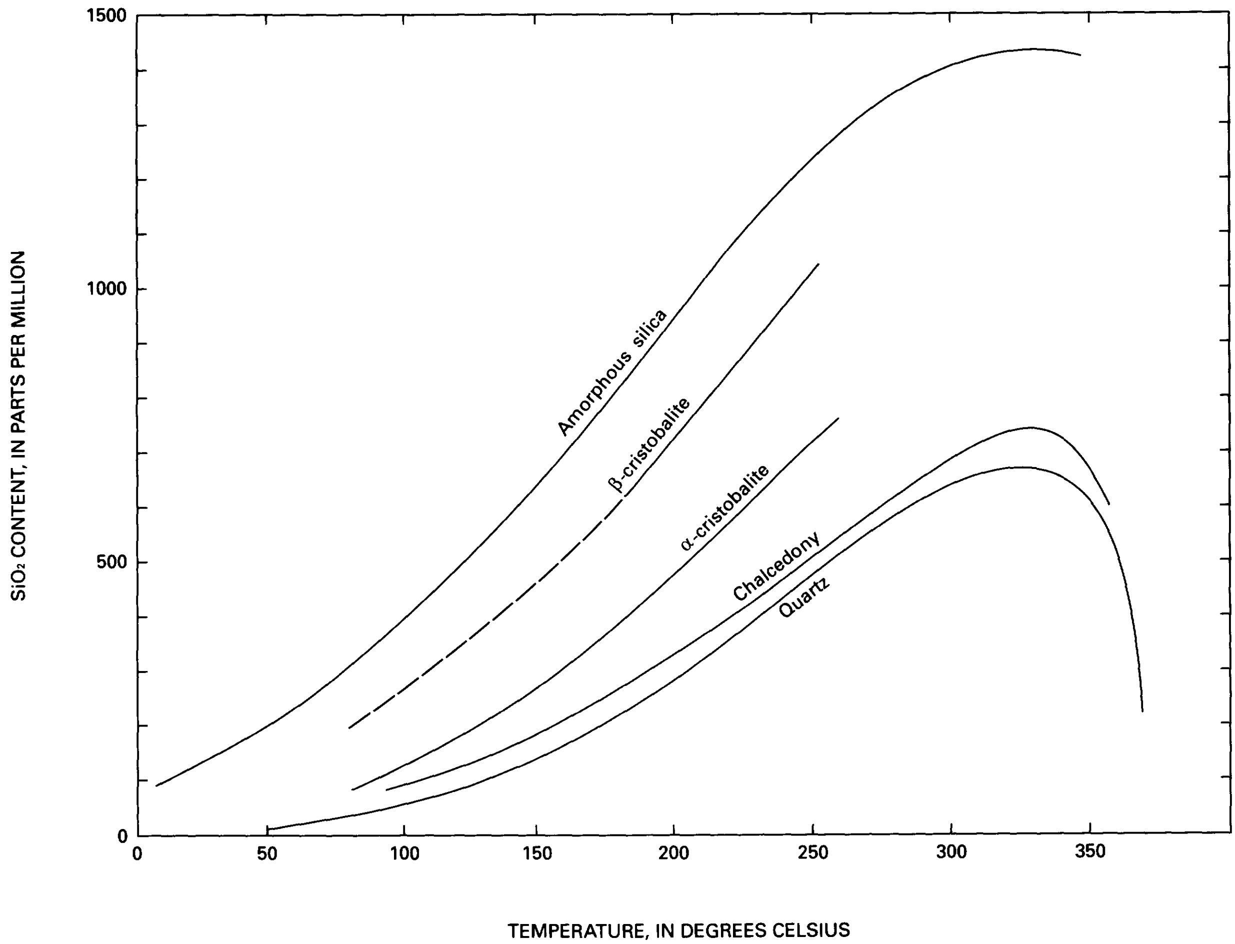


**Figure 2.** Solubilities of common silica minerals in water as a function of temperature.

**Table 2.** Contents of gold and associated elements in opaline sinters of Yellowstone National Park, Wyoming

[Short-wavelength-radiation emission-spectrographic analyses in parts per million. G.B., Gibbon Basin; G.C., Gibbon Canyon; H.L., Heart Lake Geyser Basin; L.B., Lower Geyser Basin; M.B., Midway Geyser Basin; N.B., Norris Geyser Basin; U.B., Upper Geyser Basin; W.T., West Thumb Geyser Basin; Y.L., Yellowstone Lake; Y.R., Yellowstone River. Do., ditto]

| Field No. | Description | Au | As | B | Hg | Sb | Tl | Zn |
|---|---|---|---|---|---|---|---|---|
| (66)–220 | Myriad Springs, organic matter, U.B. | <0.2 | 100 | — | 3 | 20 | <1 | 5 |
| (66)–163 | Silica gel, White Creek, L.B. | <.1 | 300 | 70 | 1,000 | 10 | 2 | 10 |
| Y–2–16 ft | Drill core, –16 ft, L.B. | <.1 | 1.5 | 200 | 3 | 15 | 1 | 3 |
| Y–7–½ ft | Biscuit Basin, U.B. | <.1 | 10 | 300 | 1.5 | 15 | 3 | 15 |
| Y–13–1 ft | Porcupine Hills, L.B. | <.1 | 2 | 150 | — | — | 3 | 15 |
| 71–3 | Mud volcano, Y.R. | <.1 | 17 | — | 22 | <2 | <1 | 9.4 |
| 71–19 | Sinter, E. of Giant, U.B. | <.1 | 1,000 | — | <2 | 68 | <1 | — |
| 71–25b | do | <.2 | 100 | 50 | 2 | 150 | <1 | 10 |
| 71–32 | Sinter, mud volcano, Y.R. | <.2 | 30 | — | 5 | 150 | <1 | 9.4 |
| 72–13 | Concretionary sand, N.B. | <.1 | 1,000 | 20 | 14 | 315 | 2.1 | 1.1 |
| 73–2 | Below Glade Geyser, H.L. | <.1 | 31 | — | 135 | 40 | 1.7 | 8.8 |
| 73–4 | Spike Geyser, H.L. | <.1 | 280 | — | <2 | 286 | 1.4 | .81 |
| 73–7 | Spouter near Spike, H.L. | <.2 | 30 | — | <2 | 300 | 1.4 | 7 |
| 75–7C | Sinter below W.T., Y.L. | <.1 | 65 | — | 17 | 110 | <1 | 52 |
| 75–24 | Geyser eggs, N.B. | <.1 | 70 | 50 | <2 | 310 | <1 | 2.6 |
| 75–29 | Gibbon Hill Geyser, G.B. | <.1 | 8.3 | — | <2 | 365 | <1 | 2.2 |
| 76–16b | Butte Spring, Y.L. | <.1 | 61 | — | <2 | 60 | <1 | 7 |
| 76–23a | Crater Hills Geyser, Y.R. | <.1 | 48 | — | 13 | >500 | >1 | 2.8 |
| 76–26c | Rabbit Creek, M.B. | <.2 | 20 | — | 1 | 100 | 5 | 3 |
| 78–3f | Hydrophane Spring, N.B. | <.2 | 50 | — | 12 | 150 | .31 | 36 |
| 78–9 | S. of Butte Spring, Y.L. | <.1 | 62 | — | <2 | 21 | <1 | 66 |
| 78–14b | Turbid Lake NE. of M.B. | <.1 | 37 | — | <2 | 110 | <1 | 1.7 |
| 82–2a | Dantes, Sylvan Spring, G.B. | .58 | 61 | 64 | 180 | 180 | 1.6 | 2.5 |
| 82–2b | do | .74 | 44 | 12 | 350 | 350 | 2.8 | 36 |
| 82–2a2 | do | .66 | 27 | >100 | 320 | 320 | 4.9 | 8.8 |
| 84–6a | Former vent, Graceful Geyser, N.B. | <.1 | 7,000 | 200 | 5 | 300 | <1 | 7 |
| 84–6 | Vent, Graceful Geyser, N.B. | <.1 | 1,000 | 500 | 10 | 500 | <1 | 5 |
| 84–5 | Graceful Geyser, discharge approx 30 ft E. of vent, N.B. | <.1 | >50,000 | 30 | 2 | 500 | <1 | 20 |
| 84–3 | Graceful Geyser, 80 ft E., N.B. | <.1 | >50,000 | 20 | 2 | 700 | <1 | 15 |
| 84–7 | Beryl Spring, above water, G.C. | <.1 | 500 | 150 | 5 | 150 | <2 | 10 |
| 84–8 | do | 10 | 150 | 70 | 50 | 150 | 50 | 10 |
| 84–9 | Beryl Spring, bottom deposits, G.C. | 3 | 150 | 70 | 30 | 150 | 15 | 10 |
| 84–9a | Beryl Spring, gray sinter, G.C. | 7 | 200 | 50 | 2 | 200 | 100 | 7 |
| 84–10 | Old sinter, hydrophane, N.B. | <.1 | 100 | 50 | 2 | 150 | <1 | 1.5 |

earthquake. The spring broke out on a gently sloping hillside in a mature pine forest, killing all trees within 6 to 13 ft of the present large pool; other trees nearby were soon killed by hot ground. The first detailed map of the hydrothermal features in the Sylvan Springs area, showing the relation of Dantes Inferno to other hot springs, appears to have been that by Hutchinson (1978). Dantes Inferno, which is the largest spring vent now in the area, is about 350 ft southwest of Evening Primrose, the only previously named feature on Hutchinson's map.

Fournier periodically collected water samples from Dantes Inferno for chemical analyses over a 12-yr period, starting in 1962. All samples contained more than 600 ppm $SiO_2$ and were greatly supersaturated with respect to amorphous silica at the temperature of the pool (for example, see sample YF426 of Thompson and others, 1975, p. 40). When first observed, the water in the pool had a characteristic opalescent-blue color caused by the light-scattering properties of suspended colloidal silica particles, much like that of former Coral Spring in Norris Basin (White and others, 1988, fig. 9). The water that is presently discharged from the pool is still supersaturated with respect to amorphous silica and has the same characteristic opalescent-blue color.

Samples of sinter collected by Fournier in 1962 for NA analyses contained 0.813 and 0.857 ppm Au (table 1). Samples of sinter collected by White and Hutchinson in 1982 for SWR analysis (samples 82–2a, 82–2b, 82–2, table 2) contained from 0.58 to 0.74 ppm Au. The gold is evidently contained within amorphous silica (opal) and elemental sulfur that become attached to the sides of the pool and to the limbs of pine trees partly immersed in the pool. The deposit is thickest at the pool surface and thins to nearly 0 at depths of 1 ft. Silica gel is also precipitating slowly as a floc on the bottom of the pool and on its discharge apron.

Many investigators have suggested that silica-gold colloids may be important in the formation of gold deposits (for example, Boydell, 1924; Lindgren, 1936; Frondel, 1938; Boyle, 1979). Fournier (1985) suggested that the gold in Dantes Inferno (identified only as a spring appearing in a pine forest on the southwestern margin of Gibbon Meadows after the Hebgen Lake earthquake) could have been incorporated into colloidal silica particles that were forming at depth, and then transported to the surface. Amorphous silica that precipitates from water commonly forms a floc (or silica gel), and this floc may eventually be transformed into quartz, as previously discussed. The common association of gold with quartz in veins may partly result from the original adsorption of gold particles onto flocculated silica.

To test these possibilities, a small surging spring in Norris Basin, later called "Porkchop," was monitored sporadically from 1947 to 1989 as it evolved to a geyser, then a wet fumarole (1987), and eventually to a hydrothermal eruption crater that self-destructed on September 5, 1989. Its early evolution was described and illustrated by White and others (1988, figs. 11–13), who just missed the culminating self-destruction. Samples of silica mud and opaline sinter collected in 1988 and 1989 were analyzed for gold by the SWR method, but none was found. A geyser in Crater Hills (sample 76–23a, table 2), west of the Yellowstone River, was acidic, high in Cl and $SO_4$. This sample was checked for Au on the chance that enrichment might be found, but its Au content was less than 0.1 ppm.

## Chalcedonic Sinter Deposits

Stream-rounded cobbles and pebbles of chalcedonic sinter are sparsely but widely distributed in late Pinedale kame deposits in Yellowstone National Park. These cobbles were preserved in the glacial deposits because of their hardness and fine-grained interlocking crystals. Subareal amorphous sinter deposits formed as a result of pre-Pinedale hot-spring activity. These early sinters were buried by subsequent sinter resulting from continuing hot-spring activity. The buried amorphous sinter was converted by diagenesis to chalcedony, while amorphous sinter continued to be deposited at the surface of the hydrothermal system, as previously discussed. Late Pinedale glaciation stripped off and finely pulverized the friable opaline sinter cap but preserved the hard, more resistant chalcedonic sinter as rounded cobbles. The precise positions of the earlier spring vents are generally uncertain, but some present thermal activity generally continues in the area where concentrations of "glacial" chalcedonic cobbles are found. The common association of chalcedonic cobbles with present hot springs is evidence that many areas of active springs also had an earlier history of pre-Pinedale activity.

Characteristic mobile elements in chalcedonic sinter (table 3) are less abundant than in opaline sinter. This generalization is difficult to prove for any one sample but is strongly indicated by comparing the As, Hg, Sb, and Tl contents listed in tables 2 and 3. The principal examples of inplace chalcedonic sinter listed in table 3 are samples 71–2, 71–13, 72–1c, 73–10a, 75–20a, 76–25f, and 78–33a; a few other samples are of rounded cobbles of float.

## Gold and Associated Elements in Miscellaneous Spring Deposits

Table 4 lists a few analyses of nonsiliceous chemical precipitates, including Mn-rich travertine, and Fe- and As-rich sulfides deposited from acidic waters. The Au contents of these samples are all below 0.1 ppm, and As and Sb contents vary widely.

Travertine is sparse in Yellowstone caldera, presumably because carbonate rocks are rare below the caldera floor. $CaCO_3$, along with most alkaline-earth carbonates, increases in solubility with decreasing temperature. Other factors, such as pH and total dissolved $CO_2$ content, can overrule the above generalization. An important factor contributing to when and where carbonates precipitate is loss of $CO_2$ during decompressional boiling of an ascending fluid. Mn, Fe, and Sr are commonly associated elements in travertine. Oxides of manganese and, to a lesser extent, iron tend to adsorb other ore elements typical of epithermal gold deposits, such as W, Cd, and base metals.

The arsenic contents of some hot-spring deposits are high; arsenic commonly precipitates initially as amorphous yellow and red sulfides from slightly acidic, gassy, sulfur-bearing springs. Springs named Realgar and Orpiment in Norris Basin (White and others, 1988, p. 53–54) have a pH of 3 to 6 and are only moderately hot. These springs have precipitated amorphous yellow and red arsenic sulfides that resemble orpiment (yellow when thin) or realgar (red when thick). Although all tested precipitates are X-ray amorphous, they probably will crystallize over time.

Some spring deposits are high in elemental sulfur (White and others, 1988), and pyrite and marcasite commonly are present in veins and as coatings. Relatively high concentrations of As, Tl, and base metals tend to coprecipitate with pyrite and marcasite (table 4).

**Table 3.** Contents of gold and associated elements in chalcedonic sinter of Yellowstone National Park, Wyoming

[Short-wavelength-radiation emission-spectrographic analyses in parts per million. E.P., Elk Park; H.L., Heart Lake Geyser; M.B., Midway Geyser Basin; N.B., Norris Geyser Basin; Y.C., Yellowstone Canyon]

| Field No. | Location | Au | As | B | Hg | Sb | Tl | Zn |
|---|---|---|---|---|---|---|---|---|
| 71–2 | SW. of Artists Point, in place, Y.C. | <0.1 | 760 | — | <2 | 85 | 20 | 22 |
| 71–7 | Float, N.B. | <.1 | 20 | — | <2 | 120 | <1 | .6 |
| 71–13 | Geyserite, SW. of Artists Point, in place, Y.C. | <.1 | 73 | — | <2 | 39 | <1 | 1 |
| 71–17 | Float, N.B. | <.1 | 10 | — | <2 | <2 | <1 | 1.6 |
| 72–1c | Chalcedony-opal sinter, N.B. | <.1 | 54 | — | <2 | 120 | <1 | 21 |
| 73–10a | Chalcedonic sinter, in place, H.L. | <.1 | 64 | — | <2 | <2 | <1 | .7 |
| 75–20a | Inspiration Point, in place, Y.C. | <.2 | 61 | — | <2 | 29 | <1 | 3.4 |
| 76–25e | Inclusion, late Pinedale, E.P. | <.1 | 68 | — | <2 | — | — | — |
| 76–25f | In place, E.P. | <.2 | 30 | — | <1 | 50 | <1 | 10 |
| 76–26a | Float, Rabbit Creek, M.B. | <.1 | <2 | — | 10 | 2 | <1 | 4.8 |
| 78–33a | Basal hydrophane, spring, N.B. | <.1 | 100 | 300 | 2 | 200 | <1 | — |

## Gold and Associated Elements in Miscellaneous Materials Collected at Shallow Depths

Table 5 lists miscellaneous samples of sediment collected at shallow depths, some of which had no known direct contact with hydrothermal systems. Four samples of unaltered "obsidian sand" (74–1a through 74–2c, table 5) were collected for SWR analysis with the aim of establishing background levels of elements in recent rhyolitic sedimentary deposits underlying Upper and Lower Geyser Basins in places where no recognized hydrothermal activity is known. In these obsidian sands, arsenic occurs slightly below or near the background level found in most rocks, ranging from about 10 to 30 ppm; Hg, Sb, and Tl are all below the detection limits by common analytical methods, and Zn is near the background level for siliceous volcanic rocks.

Sample 68–1 (table 5), an altered mid-Tertiary volcanic rock from north of the caldera margin, is related to the vapor-phase activity of Washburn Hot Springs. Mercury is the principal anomalous trace element. It is normally high in surface acidic pools.

Sample 75–26b, containing 0.53 ppm Au, is of special interest because it is one of the very few examples of gold-bearing material that had not been recognized in Fournier's search by NA analysis (table 1). In early mapping, the rock was called a chalcedony-cemented "quartzite" or arkose (White and others, 1988, p. 11–12) that contained stream-rounded quartz grains, feldspar that includes hydrothermal K-feldspar, and an absence of original volcanic glass (recognizable from relict textures). This chalcedonized stream sediment does not contain debris from the younger lava flows but consists entirely of fragments best explained by derivation from Yellowstone ash-flow tuffs. This observation provides some evidence that the relatively young lavas now present in the immediate area of the park were absent when the stream sediment was deposited. These and other characteristics (White and others, 1988, p. 11–13) indicate that this material is from the core of a former chalcedonic sinter terrace from which the original capping of sinter was completely stripped by pre-Pinedale glaciers.

## Gold and Associated Elements in Hydrothermal Eruption Craters

Abundant hydrothermally altered debris was ejected from 9 or 10 hydrothermal eruption craters around the northern part of Yellowstone Lake that ranged in diameter from 150 ft to as much as 2 mi long and ⅔ mi wide (table 6). Many of these craters formed near the end of the Pinedale glaciation, when the lake was partly filled with ice (Muffler and others, 1971). The largest crater (Mary Bay) had not yet been recognized in 1971 as an explosion crater, even though its east half is well preserved as a "half-crater," first mapped and described briefly by Richmond (1976, 1977).

Smaller craters, about 0.4 mi or less in diameter, erupted various hydrothermally cemented clastic materials and glacial debris, broken into angular blocks or, in part, mixed with uncemented clastic pebbles and cobbles. In general, this uncemented debris was probably erupted from shallow depth, thereby explaining the absence of cementation. Well-cemented debris occurs in angular blocks, presumably from greater but unknown depths and fractured by explosive force.

The largest of the Mary Bay craters erupted thoroughly cemented volcaniclastic debris and massive rhyolite flows that were broken into angular blocks, as much as 3 ft in diameter. Hydrothermally altered porphyritic rhyolite is surprisingly low in As, Sb, Hg, and Tl. In this rock, large feldspar phenocrysts were fractured, the fractures were filled by quartz veinlets, and the remaining feldspar

**Table 4.** Contents of gold and associated elements in miscellaneous spring deposits of Yellowstone National Park, Wyoming

[Short-wavelength-radiation emission-spectrographic analyses in parts per million. L.B., Lower Geyser Basin; N.B., Norris Geyser Basin; U.B., Upper Geyser Basin; Y.R., Yellowstone River. Do., ditto]

| Field No. | Description | Au | As | B | Hg | Sb | Tl | Zn |
|---|---|---|---|---|---|---|---|---|
| W–209 | Sulfur "cinders," Cinder Pool, N.B. | <0.2 | 500 | <2 | 20 | 700 | 7 | >100 |
| W–706a | Mn travertine, hillside, U.B. | <.1 | >5,000 | <2 | — | .7 | 50 | 1.5 |
| W–1130–1 | do | <.1 | 32 | — | 4.5 | <.2 | <1 | 1.8 |
| W–1130–3 | do | <.1 | <2 | — | <2 | 96 | <1 | 6.2 |
| (66)–3 | Mn travertine, Steady Geyser, L.B. | <.2 | 60 | 3 | 1.5 | 10 | 150 | 30 |
| 68–6 | Petrified wood, Ebony Geyser, N.B. | <.1 | 90 | — | <2 | 152 | .6 | 5.6 |
| 69–4 | Orpiment Spring, amorphous $Sb_2S_3$, N.B. | <.1 | >1,000 | — | 11.4 | 33 | 55 | .7 |
| 69–8b | Native sulfur, $FeS_2$, Sulphur Cauldron, Y.R. | <.1 | 102 | — | 70 | <2 | <1 | 36 |
| 76–28 | Conophytons (organisms), L.B. | <.2 | 70 | — | 2 | 70 | <1 | 3 |
| (66)–114 | Amorphous $As_2S_3$, Realgar Spring, N.B. | <.1 | >2,000 | 7 | 45 | 30 | 7 | 10 |
| 82–4a | Pyrite veinlet, Echinus Geyser, N.B. | <.1 | >1,000 | — | 66 | 340 | >100 | >100 |
| 82–4b | Marcasite veinlet, Echinus Geyser, N.B. | <.1 | >1,000 | — | >2 | 360 | >100 | >100 |
| YM–910 | Marcasite-pyrite veinlet, Echinus Geyser, N.B. | <.1 | >1,000 | <2 | 90 | 400 | >100 | 500 |
| YM–911 | Pyrite-marcasite veinlet, Echinus Geyser, N.B. | <.1 | >1,000 | <2 | 90 | 500 | >100 | 1,000 |

or its argillic replacements were leached, in part leaving webs of veinlets of small quartz crystals enlarged by overgrowth of euhedral hydrothermal quartz. Some quartz crystals containing fluid inclusions, as much as 2 mm long and 1 mm wide, were examined by John Batchelder (written commun., 1980), who found that the fluid inclusions homogenized to liquid on the heating stage at 287°±3°C. Freezing temperatures of eight fluid inclusions were uniformly near 0°C, indicating salinities near 0.0 weight percent NaCl equivalent. If no ice cover was present at the time the fluid inclusions formed while boiling conditions prevailed at all depths (no pressure correction is required), these homogenization temperatures indicate explosive ejection from depths near 3,000 ft. Bargar and Fournier (1988), however, found much variation in fluid-inclusion homogenization temperatures at specific depths in the core of drill hole Y–13. These and other high fluid-inclusion homogenization temperatures found in core from other research drill holes in Yellowstone (White and others, 1975) are best explained by thick ice cover of as much as 1,300 ft above the present ground surface during glaciation. Thus, ice cover of unknown thickness seems likely, and the depth below the present ground surface cannot be reliably estimated.

## Gold and Associated Elements in Core from Drill Holes Y–12 and Y–13, Norris and Lower Geyser Basins, Yellowstone National Park

Drill hole Y–12 is located at the northern margin of Norris Geyser Basin, and drill hole Y–13 between the two western Porcupine Hills in Lower Geyser Basin (see White and others, 1975, map locations and physical conditions of the drill holes).

The location of drill hole Y–12 was considered favorable for high temperatures because it was near hydrothermally active Porcelain Terrace (White and others, 1988, pl. 1). This hole was drilled in the massive footwall ash-flow tuff of Porcelain Terrace, and although high temperatures were measured, few fractures and veins were penetrated. Contents of gold and associated elements determined by the SWR method are generally low in core samples from this drill hole; no gold was found within the detection limit for the method (0.1 ppm; table 7). A sample of altered Yellowstone ash-flow tuff from about −50.7-ft depth shows considerable enrichment in As, Sb, Hg, and Tl above background levels. Thus, gold may also be enriched, though still below 0.1 ppm. The concentration of zinc, the most sensitive indicator for base metals, is highest near the bottom of the hole (−1,047.5 ft). Apparently, zinc was slightly mobile in the deep Norris Basin environment where 237.5°C was measured (White and others, 1975). Other mineralized zones near −180 and −481 ft are slightly enriched in silver (max 0.2 ppm).

Typical core from drill hole Y–13 (table 7) was analyzed by the SWR method for gold and associated volatile elements. Gold within the detection limit of 0.1 ppm was not found, but silver and associated elements generally show some enrichment. This observation suggests that gold was also enriched above the background level of 1 ppb but was less than 0.1 ppm. Arsenic and antimony are commonly enriched slightly above the background levels, and arsenic is especially enriched from −155- to −215-ft depth. Hg and Tl are generally not found, but some Hg

**Table 5.** Contents of gold and associated elements in miscellaneous near-surface materials from well-established depths, Yellowstone National Park, Wyoming

[Short-wavelength-radiation emission-spectrographic analyses in parts per million. N.B., Norris Geyser Basin; U.B., Upper Geyser Basin; W.S., Washburn Springs; Y.L., Yellowstone Lake. Do., ditto]

| Field No. | Description | Au | As | Hg | Sb | Tl | Zn |
|---|---|---|---|---|---|---|---|
| 68–1 | Sulfur and clay in mudpot, W.S. | <0.1 | 14 | 140 | <2 | <1 | 34 |
| 74–1a | Obsidian sand, –0.5 m, unaltered, U.B. | <.1 | 14 | <2 | <2 | <1 | 65 |
| 74–1c | do | <.1 | 26 | <2 | <2 | <1 | 63 |
| 74–2a | Obsidian sand, –0.7 m, U.B. | <.1 | 12 | <2 | <2 | <1 | 53 |
| 74–2c | Obsidian sand, –2.0 m, U.B. | <.1 | 9.6 | <2 | <2 | <1 | 68 |
| 75–15f | Opal-cemented sediment, N.B. | <.1 | 134 | <2 | 20 | 2.1 | 94 |
| 75–19 | Opal-cemented lake sediment, S. of Squaw Lake, Y.L. | <.1 | >1,000 | <2 | 360 | >100 | >100 |
| 75–25e | Opaline sediment, N.B. | <.1 | 8.3 | <2 | <2 | <1 | 2.4 |
| 75–26b | Chalcedony-cemented sediment, pre-late Pinedale, N.B. | .53 | 13 | <2 | 13.5 | <1 | 1.5 |

occurs near the surface, and Tl is slightly higher in samples near –150- to –215-ft depth.

Both drill holes Y–12 and Y–13 show much hydrothermal alteration but little veining or $SiO_2$ enrichment. In view of the limited number of holes we were permitted to drill in central regions of hydrothermal upflow in the park, the absence of Au contents greater than 0.1 ppm in drill core is not too surprising. Although gold was not detected by the SWR method in any Yellowstone drill core, anomalous concentrations of silver and associated elements strongly suggest that gold is also enriched above the background level. The very high gold contents of some hot-spring sinters (table 1) are especially intriguing, but the ground surrounding these springs was not tested by drilling.

## GOLD IN SAMPLES FROM STEAMBOAT SPRINGS, NEVADA

White and Heropoulos (1983) and White (1985) concluded that Steamboat Springs, Nev., is a genuine example of epithermal Au-Ag deposits formed by hot springs in the Great Basin. Some older deposits, largely veins in and below volcanic rocks of central Nevada, are about 43 to 34 Ma old. Three younger groups of volcanic rocks associated with epithermal gold are approximately 34–17, 17–6, and less than 6 Ma old. Each group, plotted by age, is approximately arcuate in form and shows that magmatism migrated westward over time. Steamboat Springs, a member of the youngest group, has been active through much, but possibly not all, of the past 3 Ma. Gold and silver were deposited early at Steamboat Springs, and transport and deposition have continued to the present with no obvious break. The deposits are not mined today primarily because of existing high temperatures and for environmental reasons.

### Gold in Material Precipitated from Hot Springs

The Au contents of deposits from different springs at Steamboat differ by at least three orders of magnitude, and by a factor of about 25 for samples collected from the same spring (No. 24) at different times (samples W–37eh and W–50, both from spring 24, table 1). Sample W–50 was composed almost entirely of fine-grained black mud that contained tiny radiating clusters of microscopic stibnite needles, as well as small irregular grains of yellow-orange amorphous metastibnite ($Sb_2S_3$). Much $FeS_2$ is present in an amorphous silica floc. This sample contained almost no foreign windblown material and was analyzed at least four times by three methods.

Spring 24 tended to flow at times of high total discharge (White, 1968, pl. 4), particularly when general water levels within the main terrace were high and the water was turbid from suspended sediment. Most of the metallic elements in the sediment were associated with siliceous floc. We have no data about dissolved metals still in true solution. The detailed records for individual springs indicate that each spring is unpredictable (White, 1968, bottom of pl. 4 and p. C–35 to C–37). Only springs 2, 3, 8, and 50 maintained continuous but changing rates of discharge throughout the 7 years of detailed monitoring.

The pattern of random changes in individual springs (see White, 1968, fig. 19) is best explained by very high $SiO_2$ contents at high temperatures, much of which precipitates as a floc below the surface, clogging individual channels as temperatures decrease upward. Excess heat boils off as steam as the water pressure decreases upward. Much gold presumably precipitates on the flocculated silica, which may then recrystallize over time to cristobalite and eventually to chalcedony at depths of 10 to 300 m or more. Flocculated silica is brought up in suspension during periods of high discharge and agitation. This observation

**Table 6.** Contents of gold and associated elements in samples from hydrothermal eruption craters of Yellowstone National Park, Wyoming

[Short-wavelength-radiation emission-spectrographic analyses in parts per million. L.B., Lower Geyser Basin; M.B., Mary Bay; W.T., West Thumb Geyser Basin; Y.L., Yellowstone Lake]

| Field No. | Location | Au | As | B | Hg | Sb | Tl | Zn |
|---|---|---|---|---|---|---|---|---|
| (66)–115 | Fine sandstone in clastic dike, Pocket Basin, L.B. | <0.1 | 30 | — | <2 | 13 | <1 | 9 |
| 75–6a | Cemented sand, Squaw Lake, Y.L. | <.1 | 15 | — | <2 | 12 | <1 | 40 |
| 75–15c | Leached feldspar porphyry, M.B., Y.L. | <.2 | 100 | — | <1 | 3 | 2 | 15 |
| 75–15f | Feldspar porphyry, bladed calcite, quartz, M.B., Y.L. | <.1 | 134 | — | <2 | 28 | 2.1 | 94 |
| 75–20a | Feldspar porphyry and pyrite, M.B., Y.L. | <.1 | 61 | — | <2 | 29 | <1 | — |
| 76–1a | Feldspar porphyry, vuggy quartz, M.B., Y.L. | <.1 | 8 | — | <2 | <2 | <1 | — |
| 76–1b | Volcanic clasts, zeolites, Duck Lake, W.T. | <.1 | 10 | — | <2 | <2 | <1 | 1.6 |
| 76–1c | Feldspar porphyry, leached + pyrite, M.B., Y.L. | <.1 | 100 | — | 13 | 49 | 2.4 | — |
| 76–14b | Chalcedony-pyrite, Butte Quarry, Y.L. | <.1 | 97 | — | <2 | 9 | 2.0 | 32 |
| 76–15a | Chalcedony vein fragment, SE. of Butte Quarry, Y.L. | <.1 | 6 | — | <2 | 14 | 1.2 | 3 |
| 78–3e | Chalcedony-wairakite vein, Squaw Lake, M.B., Y.L. | <.1 | 23 | — | <2 | <2 | 1.6 | 31 |
| 78–7a | Banded chalcedony vein, M.B., Y.L. | <.1 | 15 | <2 | 1.5 | 7 | 1.6 | 7 |
| 78–17 | Banded chalcedony vein, Butte Quarry, Y.L. | <.1 | 6 | 150? | <2 | <2 | <1 | — |
| 80–9 | Chalcedony-calcite-pyrite vein, M.B., Y.L. | <.1 | 12 | — | <2 | <2 | <1 | 26 |

may also explain why $Sb_2S_3$ occurs in two distinct forms, as well-crystallized clusters of tiny needles (stable) and as an amorphous orange-colored deposit (metastable). In general, the color of a sediment in the springs at Steamboat Springs is a good qualitative indication of its relative Au content, as well as of Sb and $FeS_2$. The differences in Au contents among springs 24, 27, and 21 appear to be real.

## Gold and Associated Elements Deposited in Three Drill Holes at Steamboat Springs, Nevada

The Au and Ag contents of core from drill hole GS–5 were summarized by White (1981, 1985) and White and Heropoulos (1983), but the contents of associated elements from this hole have not been discussed in detail. None of the minor-metal data from drill holes GS–2 and GS–6 have been previously published. The generalized geology and locations of these holes are shown in figure 3. The detailed stratigraphy of each hole was reviewed by White and others (1964, p. B13–B17), and the contents of trace elements and silver are listed in table 8.

Hole GS–2 was drilled on the High Terrace, about 3,000 ft northwest of the Main Terrace. The High Terrace has a present water level 40 to 50 ft below the surface; water drains mainly northward below ground to Truckee Meadows. Water near drill hole GS–5 on the Main Terrace also flows northward as well as eastward to Steamboat Creek (fig. 3). Drill hole GS–6 is located on Sinter Hill southwest of GS–2 and is clearly in the older part of the drilled system; its collar is about 116 ft in altitude above that of GS–2. Present water in the hole is hot but dilute; its water level is about 68 ft below the local surface, and it flows slowly northward.

In order of increasing age of near-surface hot-spring deposits, the area where hole GS–5 was drilled is the youngest and is still active. Hole GS–2 was drilled on the High Terrace northwest of GS-5. In this area, water also is still circulating below ground but has not discharged at the surface for much of the past 100 ka (White, 1968). GS–6 is in the oldest cover of these three drill holes; it penetrates into basaltic andesite (early Pleistocene) at –91- to –133-ft depth, with no evidence for a nondepositional time gap at either contact. The age of fresh basaltic andesite in the area is tightly constrained near 2.53 Ma (Silberman and others, 1979). The basaltic andesite in the drill hole is hydrothermally altered but shows clearly recognizable relict textures of the fresh rock, with former plagioclase replaced by monoclinic hydrothermal K-feldspar. The potassium content of the feldspar increased from about 2.5 to 10.9 weight percent during alteration, and the resulting hydrothermal K-feldspar yielded an alteration age of 1.1 Ma.

Drill hole GS–5 contains gold detected by the SWR method to depths near –231 ft; at greater depths, gold is below the detection limit (then 0.2 ppm). Silver is dispersed throughout, especially from –113- to –360-ft depth, and its content generally increases downward. Pyrargyrite ($(Ag_2S_3)_3 \cdot Sb_2S_3$) is the only recognized silver mineral. As,

**Table 7.** Contents of gold and associated elements in core from drill holes Y–12 and Y–13, Norris Geyser Basin and Lower Geyser Basin, Yellowstone National Park, Wyoming

[Short-wavelength-radiation emission-spectrographic analyses in parts per million. Y–12, Norris Geyser Basin; Y–13, Porcupine Hills, Lower Geyser Basin]

| Drill hole | Depth (ft) | Au | Ag | As | B | Hg | Sb | Tl | Zn |
|---|---|---|---|---|---|---|---|---|---|
| Y–12 | –8 | <0.1 | — | 9 | — | 14 | <2 | <1 | 12.8 |
| | –13 | <.1 | — | 16 | — | 6.4 | <2 | <1 | 3.4 |
| | –22 | <.1 | — | 8.2 | — | 10 | 4.8 | <1 | 2.5 |
| | –50.7 | <.1 | — | 310 | — | 120 | 93 | 19 | 18 |
| | –52.2 | <.1 | — | 11 | — | 16 | 16 | <1 | 3.8 |
| | –80.1 | <.1 | — | 76 | — | 30 | 88 | <1 | 63 |
| | –80.4 | <.1 | <.1 | — | 5.8 | — | — | — | — |
| | –92.7 | <.1 | — | 130 | — | 15 | 15 | 1.6 | 10 |
| | –120 | <.1 | — | 190 | — | <2 | 28 | <1 | 35 |
| | –180 | <.1 | .2 | 16 | — | <2 | <2 | <1 | 26 |
| | –481 | <.1 | .12 | — | — | — | — | — | — |
| | –1,047.5 | <.1 | — | 16 | — | <2 | <2 | <1 | 140 |
| Y–13 | –1 | <.2 | — | 50 | 500 | <1 | 7 | <1 | 4 |
| | –8 | <.1 | .2 | 100 | 20 | 2 | 50 | <1 | 30 |
| | –43.4 | <.1 | <.2 | 10 | <2 | <1 | 50 | <1 | 50 |
| | –47.2 | <.1 | <.2 | 70 | <.2 | 2 | 50 | <1 | 30 |
| | –54.6 | <.1 | <.2 | 50 | <2 | <1 | 50 | 1.5 | 20 |
| | –64 | <.1 | .2 | 50 | <2 | <1 | 30 | <1 | 50 |
| | –70.9 | <.1 | .3 | 70 | 2 | <1 | 50 | <1 | 7 |
| | –84.3 | <.1 | .2 | 50 | <2 | <1 | 20 | <1 | 100 |
| | –86 | <.1 | <.2 | 20 | <2 | <1 | 30 | 1 | 70 |
| | –90.6 | <.1 | <.2 | 7 | 2 | 1 | 20 | <1 | 50 |
| | –112.4 | <.1 | <.2 | 3 | <2 | <1 | 20 | <1 | 30 |
| | –119.8 | <.1 | 1 | 50 | 2 | <1 | 30 | 2 | 70 |
| | –149.9 | <.1 | .3 | 10 | <2 | <1 | 30 | 5 | 50 |
| | –155 | <.1 | .7 | 150 | <2 | <1 | 20 | 1.5 | 30 |
| | –165 | <.1 | .7 | 100 | 2 | <1 | 10 | <1 | 20 |
| | –169.7 | <.1 | .2 | 70 | 2 | <1 | 10 | <1 | 50 |
| | –185.4 | <.1 | .5 | 100 | 2 | <1 | 15 | 2 | 70 |
| | –206 | <.1 | .5 | 50 | <2 | <1 | 10 | <1 | 30 |
| | –215.5 | <.1 | .5 | 100 | 2 | <1 | 15 | 15 | 50 |
| | –249 | <.1 | .2 | 15 | <2 | <1 | 10 | <1 | 50 |
| | –294 | <.1 | .2 | 5 | 2 | <1 | 7 | <1 | 50 |
| | –350 | <.1 | .2 | 30 | <2 | <1 | 5 | <1 | 70 |
| | –361.7 | <.1 | .2 | 30 | 2 | <1 | 10 | <1 | 50 |
| | –418.6 | <.1 | .3 | 50 | 2 | <1 | 10 | 1 | 30 |
| | –463 | <.1 | .2 | 30 | 2 | <1 | 5 | 1 | 50 |

Sb, Hg, Tl, and B are concentrated in the upper part of the hole; B and Hg contents vary only slightly below –231-ft depth. The highest Au content is 1.5 ppm, and the highest Ag content 100 ppm, from –273- to –363-ft depth. Antimony and arsenic are markedly enriched above –42-ft depth. Significant variations occur in B content down to –42-ft depth, and in Hg content in the upper 19 ft of the hole.

Gold in core from drill hole GS–2 is also enriched near the surface; it was detected to –202-ft depth. The Ag content is high throughout the core, especially below –350-ft depth. The As content is irregularly above the background level, especially above –350-ft depth, in part related to coprecipitation with iron of the associated andesite. Sb and Tl contents generally are somewhat high, especially above –200-ft depth, whereas Hg and B are mainly concentrated near the surface.

Core from drill hole GS–6 is also enriched in gold to about 1.5 ppm at –31- and –106-ft depth. As and Sb contents are irregular, showing enrichment at –106-ft depth in a veinlet that cuts basaltic andesite. The tungsten content ranges from 50 to 100 ppm in three samples, possibly coprecipitated with iron or manganese. Tungsten was not reported elsewhere in drill hole GS–6.

**Table 8.** Contents of gold and associated elements in samples from three drill holes, Steamboat Springs, Nevada, for comparison with Yellowstone National Park, Wyoming

[Short-wavelength-radiation emission-spectrographic analyses in parts per million. See figure 3 for locations. Do., ditto]

| Depth (ft) | Description | Au | Ag | As | B | Hg | Sb | Tl | Zn | W | Mn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Drill hole GS–2** | | | | | | |
| –11 | Opaline sinter | <0.1 | 0.5 | 10 | 70 | 1,500 | 700 | <3 | <15 | 150 | 1,500 |
| –27 | Chalcedonic sinter | 1 | — | 10 | 30 | 30 | 700 | <3 | <15 | — | — |
| –41a | Late-stage chalcedony vein | 2 | 10 | 200 | <2 | 15 | >2,000 | 50 | 7 | <10 | — |
| –41b | Early-stage gray chalcedony vein | 1 | 7 | 70 | 5 | 5 | 300 | 5 | 2 | <10 | — |
| –72 | Chalcedonic sinter | 2 | 20 | 200 | 20 | <10 | 150 | 20 | <15 | — | — |
| –138 | Rounded andesite cobble | <.1 | .7 | 2,000 | 2 | 10 | 100 | 10 | 70 | <10 | — |
| –175a | Early-stage dark vein | 2 | 50 | >2,000 | 3 | 20 | 300 | 15 | 200 | — | — |
| –175b | Late-stage gray vein | 1.5 | 50 | 100 | 5 | <1 | 100 | 2 | 7 | — | — |
| –202 | Late-stage gray andesite breccia | .1 | 5 | 150 | 3 | 5 | 50 | 5 | 30 | — | — |
| –244 | Andesite breccia with pyrite | <.1 | 15 | >2,000 | <2 | <1 | 50 | 2 | 15 | — | — |
| –297 | Calcite–chalcedony vein | <.1 | 7 | 700 | 2 | <1 | 30 | 1 | 70 | — | — |
| –349 | Gray vein in andesite breccia | <.1 | 7 | 700 | 2 | <1 | 30 | 1 | 70 | — | — |
| –397 | Altered granodiorite | <.1 | .5 | 150 | 30 | 5 | 30 | 2 | 30 | — | — |
| | | | | | **Drill hole GS–5** | | | | | | |
| –11 | Opaline sinter | 0.3 | 2 | 700 | 1,000 | 1,000 | 150 | <10 | <15 | — | — |
| –19 | Black opaline sinter | <.2 | .3 | 500 | 500 | 500 | 500 | 5 | <15 | — | — |
| –42 | Crystobalite sinter | .2 | .5 | 200 | 200 | <10 | 5,000 | 150 | <15 | — | — |
| –84 | Chalcedonic sinter | <.2 | <.2 | <100 | <10 | 100 | 7 | <15 | — | — | — |
| –113 | Chalcedonic alluvium | 1.5 | 30 | <100 | 15 | <10 | 50 | 5 | <15 | — | — |
| –174 | Chalcedony–calcite veins | .7 | 20 | <100 | 15 | <10 | 50 | 3 | <15 | — | — |
| –231 | do | .3 | 70 | <100 | 15 | <10 | 30 | 3 | <15 | — | — |
| –273 | do | <.2 | 100 | <100 | 20 | <10 | 30 | <3 | <15 | — | — |
| –346 | 7-ft-thick chalcedony-calcite veins | <.2 | 15 | <100 | 10 | <10 | 20 | <3 | <15 | — | — |
| –363 | Thick chalcedony-calcite veins with ruby silver. | <.2 | 100 | <100 | 20 | <10 | 20 | <3 | <15 | — | — |
| –446 | Granodiorite with ruby silver | <.2 | .7? | <100 | 15 | <10 | 20 | <3 | <15 | — | — |
| | | | | | **Drill hole GS–6** | | | | | | |
| –18 | Chalcedonic sinter | 0.2 | 0.5 | 15 | 30 | 10 | 500 | <3 | 0.7 | <10 | <0.7 |
| –31 | Vein in sinter | 1.5 | 1.5 | 700 | 150 | 100 | >2,000 | 100 | 7 | <10 | 2 |
| –54 | Cemented alluvium | <.1 | .7 | 150 | 5 | 20 | 1500 | 3 | 1.5 | 100 | 2 |
| –74 | Altered andesite flow | <.1 | 5 | 50 | 5 | 10 | 150 | 5 | 5 | <10 | 7 |
| –106a | Oldest vein, andesite | <.1 | <.2 | >2,000 | <2 | <1 | 300 | 20 | 15 | <10 | 30 |
| –106b | Middle-stage gray vein in andesite | 1.5 | 100 | 2,000 | <2 | 10 | >2,000 | 50 | 15 | <10 | 10 |
| –106c | Late-stage vein in andesite | <.1 | 5 | >2,000 | <2 | 7 | 700 | 50 | 700 | 70 | 5 |
| –134 | Volcanic breccia | <.1 | .5 | 200 | 7 | 2 | 50 | 5 | 50 | <10 | 200 |
| –160 | Vein in soda trachyte | <.1 | 2 | >2,000 | 7 | 1 | 70 | 5 | 30 | <10 | 50 |
| –170 | Arkosic alluvium | <.1 | .3 | 15 | 20 | 1 | 50 | <3 | 50 | 50 | 100 |
| –212 | Vein in granodiorite | <.1 | 1 | 700 | 5 | <1 | 70 | 3 | 15 | <10 | 50 |

## CONCLUSIONS, INTERPRETATIONS, AND SPECULATIONS

Anomalous Au contents (more than 0.1 ppm by the SWR method) occur in only 9 of 119 Yellowstone samples (tables 2–7); "enriched" samples above detection levels are listed in table 9. In these enriched samples, contents of As, Sb, Hg, B, Tl, and Zn (as a key base metal) all vary widely with respect to Au and to each other. In figures 4 and 5, respectively, Sb and As contents are plotted relative to Au for all samples of this report that are notably enriched in gold. Both Sb and As contents tend to be higher in the Au-rich samples, but the relation is far from linear. Note that the Sb and As contents of samples containing less than 0.1 ppm Au lie within the same range as for samples containing more than 0.1 ppm Au (tables 2–8). Although Au appears to be concentrated in samples rich in Sb and As, high concentrations of these two elements do not necessarily require correspondingly high Au contents in either the Yellowstone or the Steamboat Springs samples. The As content seems to vary somewhat more than Sb in the Yellowstone samples, ranging from very high (more than 50,000 ppm) to very low. Contents of As may change relative to Sb, perhaps because arsenic tends to coprecipitate with iron.

The distribution of thallium relative to gold shows a linear relation; contents of both elements increase together in Yellowstone National Park (fig. 6), but a similar plot for samples from the three Steamboat Springs drill holes does not support this concept.

One of us (D.E.W.) has observed that on a regional scale in the Western United States, background levels of both thallium and boron seem to increase westward toward the Pacific Ocean when similar materials and environments are compared, such as hot springs and oil-field brines.

The major differences between Yellowstone National Park and Steamboat Springs are: (1) Au contents are consistently higher in drill core from Steamboat than in Yellowstone Park, possibly in part because of the greater age of the Steamboat system, with more time available for hydrothermal deposition to occur; (2) Cl and $H_2S$ contents in Steamboat waters are higher; (3) a greater variety of

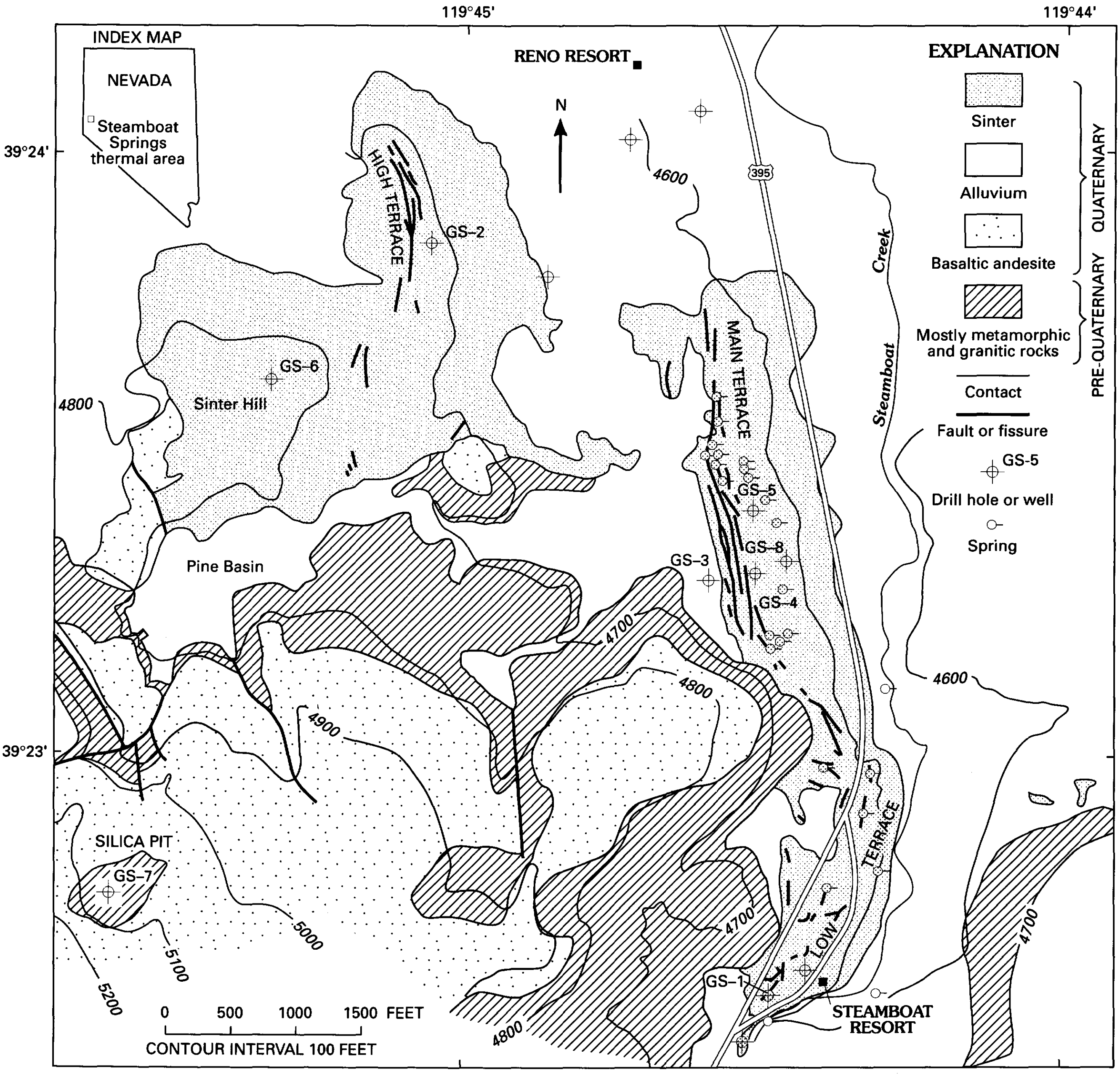


**Figure 3.** Geologic sketch map of Steamboat Springs thermal area, Nev. (modified from Schoen and White, 1965, fig. 1).

**Table 9.** Contents of gold and associated elements in samples from Yellowstone National Park, Wyoming, that are relatively gold rich

[Short-wavelength-radiation emission-spectrographic analyses in parts per million. G.B., Gibbon Geyser Basin; G.C., Gibbon Canyon; N.B., Norris Geyser Basin. Do., ditto]

| Field No. | Description | Au | Ag | As | B | Hg | Sb | Tl | Zn |
|---|---|---|---|---|---|---|---|---|---|
| 75–26b | Hydrothermal quartzite, N.B. | 0.53 | — | 13 | — | <2 | 13.5 | <1 | 1.5 |
| 82–2 | Dantes, Sylvan, G.B. | .66 | — | 27 | — | >100 | 320 | 4.9 | 8.8 |
| 82–2a | do | .58 | — | 61 | — | 64 | 180 | 1.6 | 2.5 |
| 82–2b | do | .74 | — | 44 | — | 12.5 | 150 | 2.8 | 36 |
| 82–3 | Pyrite on cobble, Steamboat Geyser, N.B. | .74 | — | 23 | — | 69 | 52 | 2.2 | 3.3 |
| 84–8 | Beryl Spring, G.C. | 10 | .3 | 150 | 70 | 50 | 150 | 50 | 10 |
| 84–8a | Beryl Spring, below water level, G.C. | 3 | .2 | 150 | 70 | 30 | 150 | 15 | 10 |
| 84–9 | Beryl Spring, gray, middle depth, G.C. | 7 | .2 | 200 | 50 | 2 | 200 | 100 | 7 |
| 84–11 | Pyrite on cobble, Steamboat Geyser, N.B. | 1.0 | .2 | 500 | 20 | — | — | — | 1.2 |

rocks are penetrated at Steamboat Springs, with more basalt and andesite than the dominant rhyolite at Yellowstone; and (4) the percentage of chalcedony-quartz-calcite veins is much greater at Steamboat Springs than in Yellowstone. Also, the strikes of dominant vein structures are clear at Steamboat Springs, making it easy to site drill holes that would intersect veins. Vertical holes at Steamboat Springs generally penetrated one to five steeply dipping vein structures; the thickest veins were as much as 7 ft thick, in contrast to Yellowstone, where veins were generally absent at sites available for drilling. Environmental and other restrictions at Yellowstone seriously limited the selection of drill sites; obvious fault and vein structures were not drilled. We suspect, but cannot prove, that siliceous veins and veinlets carrying gold and other trace elements are more abundant in the central upflow regions of the geyser basins than on the basin margins, where drilling generally was carried out for environmental reasons.

White (1985) questioned whether epithermal vein deposits in volcanic rocks differ in significant respects from sediment-hosted deposits. Of course, some veins in volcanic rocks extend down into sedimentary or metamorphic rocks. Information is unavailable on the maximum vertical extent of possible gold mineralization in Yellowstone. More information is available from Steamboat Springs, where detectable gold (more than 0.1 ppm) occurs to about −230-ft depth in drill hole GS–5 on the Main Terrace, to −200-ft depth in GS–2 on the High Terrace, and to a little more than −100-ft depth in GS–6 on Sinter Hill. If these differences are taken into account, the original cover was eroded by 200 ft on Sinter Hill and, possibly, 100 ft on the High Terrace, and so the original maximum depth of gold mineralization at Steamboat Springs was likely to have been about 250 to 300 ft below the paleosurface then existing. This depth range, if valid, is too shallow for typical epithermal veins in the Great Basin, where a depth of at least 2,000 ft is known for the Comstock Lode. Such reasoning suggests that Steamboat Springs may not be as potent as some older Great Basin systems, or that higher temperatures, deeper initial boiling, or more intimate contact with magma is essential. However, the −250- to −300-ft maximum depth of gold mineralization at Steamboat Springs is based on data from only three drill holes, which is not enough to prove consistency.

Gold in core at Steamboat Springs was detected to depths of −500 ft or more and may grade into base-metal/silver mineralization, as suggested by White and Heropoulos (1983). This observation is consistent with studies of the active New Zealand thermal systems (Browne, 1971).

Both Yellowstone National Park and Steamboat Springs provide examples of the surface expression of vein systems in which deposition of ore minerals is occurring at depth. Many convection systems, however, may not discharge directly upward as hot springs. Upflow of hot water should "mound" the water table above surrounding water levels, but this "mounding" may be too deep for discharge to appear locally. If the topographic relief is high and the water table is low (as under mountain ranges), all discharge of liquid may occur laterally, with merging of hotter and cooler waters. Such a model could explain the diverse modes of gold occurrence related to hot-spring (or hot-spring-like) activity, ranging from conservation of most metallic elements deposited in subsurface veins to wide dispersal by springs discharging on the ground surface. Evidence has been presented here to indicate that precipitated Au contents greater than about 0.1 ppm at Steamboat Springs tend to decrease downward, with a cutoff of about 0.1 ppm near a depth of 250 ft below the original ground surface. Other vein systems may have salinities that are too high (or too low) for available reduced species, or are responsive to other compositional factors that determine the maximum depth of mineralization.

Very few sediment-hosted gold deposits of the Great Basin are well categorized for maximum depth of initial mineralization. The optimum temperature range from fluid-inclusion studies is commonly near 250°C (ranging from 220° to higher than 300°C) for most vein deposits (White and Heropoulos, 1983), but fluid-inclusion temperatures for sediment-hosted deposits commonly are below 200°C (White and Heropoulos, 1983, tables 2, 3). In addition, fluid-inclusion salinities commonly exceed 1 weight percent NaCl equivalent in sediment-hosted districts, in contrast to less than 1 weight percent NaCl equivalent in many vein deposits.

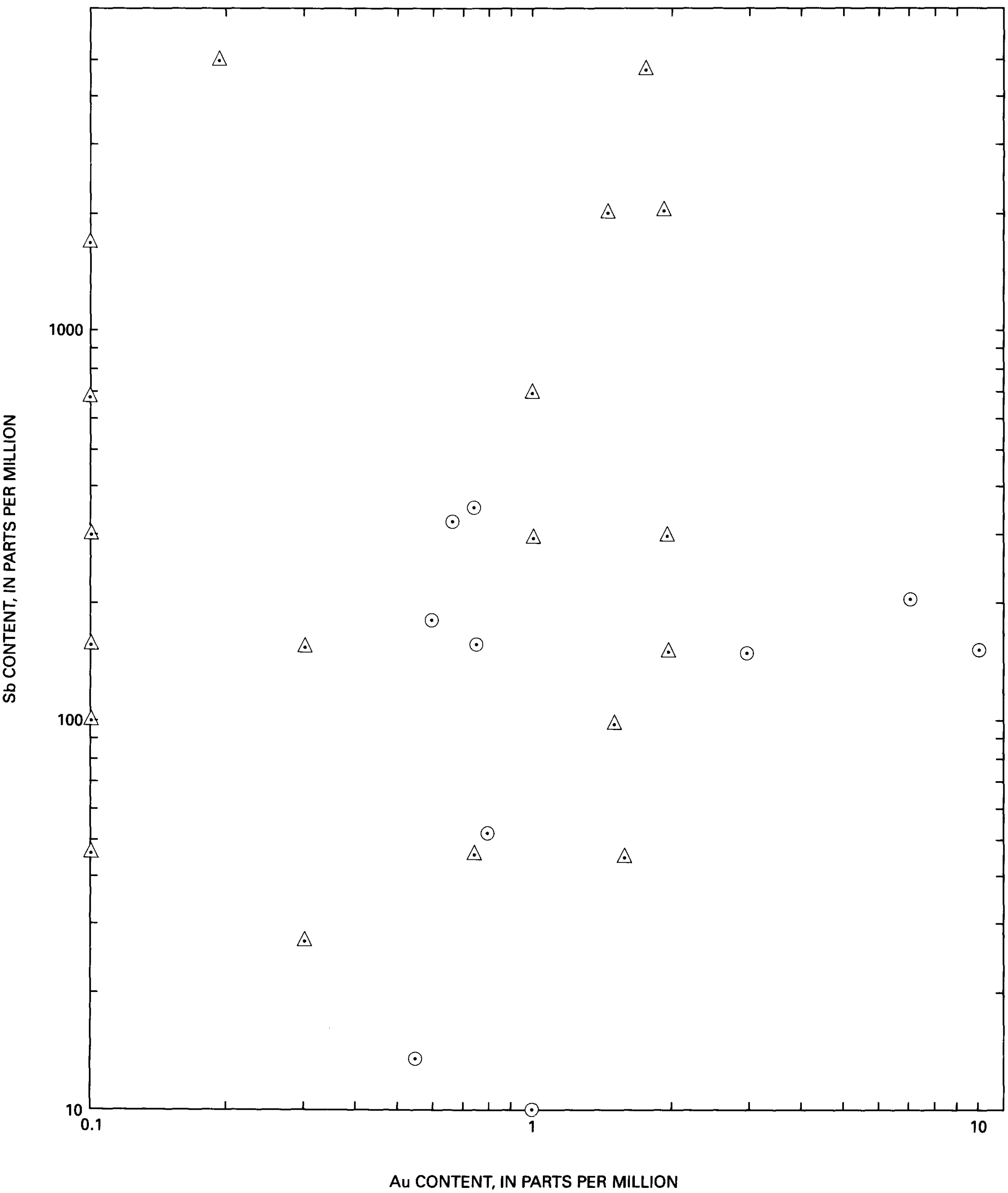


**Figure 4.** Antimony versus gold contents in samples from Yellowstone National Park (circles) and Steamboat Springs, Nev. (triangles), that contain at least 0.1 ppm Au.

The age of mineralization of many sediment-hosted districts, where known, is commonly greater than 40 Ma. Better data on ages and salinities are needed for many additional sediment-hosted gold deposits. A tentative model suggests that many of these deposits may have had upper limits to mineralization that lie below the surface, possibly owing to self-sealing by the decreasing solubility of quartz (or chalcedony) with decreasing temperature. Such a system could lose much heat upward, in large part by conduction rather than convection, and the precious metals and other trace elements could pond locally and precipitate as cooling occurred, with the water eventually discharging laterally and mixing with cooler ground water.

Can such a model be tested? Many factors must be considered, but one approach is to select active "blind" hydrothermal systems, such as Desert Peak in western Nevada (Benoit and others, 1982), for testing. Present temperatures at Desert Peak are reported (Muffler, 1979) as 208°C (measured), possibly ranging as high as about 230°C. No thermal water presently discharges at the surface, but the system could have discharged earlier in Pleistocene time when water was more abundant. The system is topographically high, and ground water presumably flows northwestward and southward. Convective circulation of thermal water, though not yet well defined, may flow in these directions. No chemical data are available on trace elements.

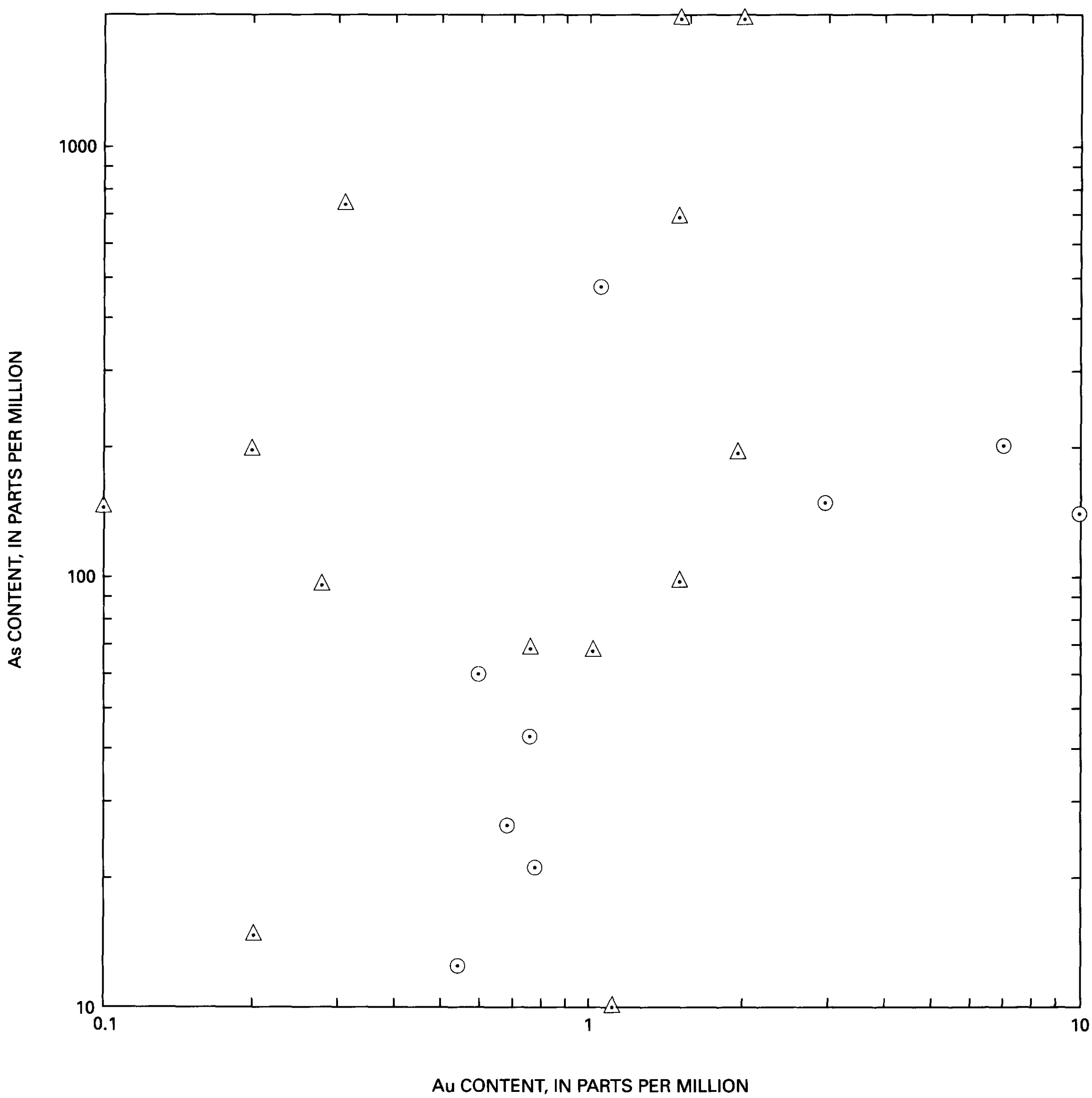


**Figure 5.** Arsenic versus gold contents in samples from Yellowstone National Park (circles) and Steamboat Springs, Nev. (triangles), that contain at least 0.1 ppm Au.

The "blind" geothermal systems southeast of the Salton Sea system in California provide other opportunities for testing the model. The Salton Sea system now has a feeble surface discharge that was surely much greater in the past when sea level was higher, covering all of the geothermal field. This system is well known for its extremely high temperatures (above 360°C), a clearly volcanic heat source, dominance of meteoric water, very high salinities, and high contents of base metals, at least in part derived from contact of brine and fine-grained sedimentary deposits.

Other "blind" convection systems not so closely related to nearby volcanic sources of heat also are present between the Salton Sea and the United States-Mexican border. At least five other presently "blind" systems have been drilled, ranging in maximum temperature from about 160° to 250°C (Muffler, 1979). Salinities are consistently less than in the Salton Sea system and are in approximate proportion to their maximum temperature. Some of these systems, as well as Cerro Prieto south of the United States-Mexican border, are rich in silver and base metals, but no reliable analyses for gold are known.

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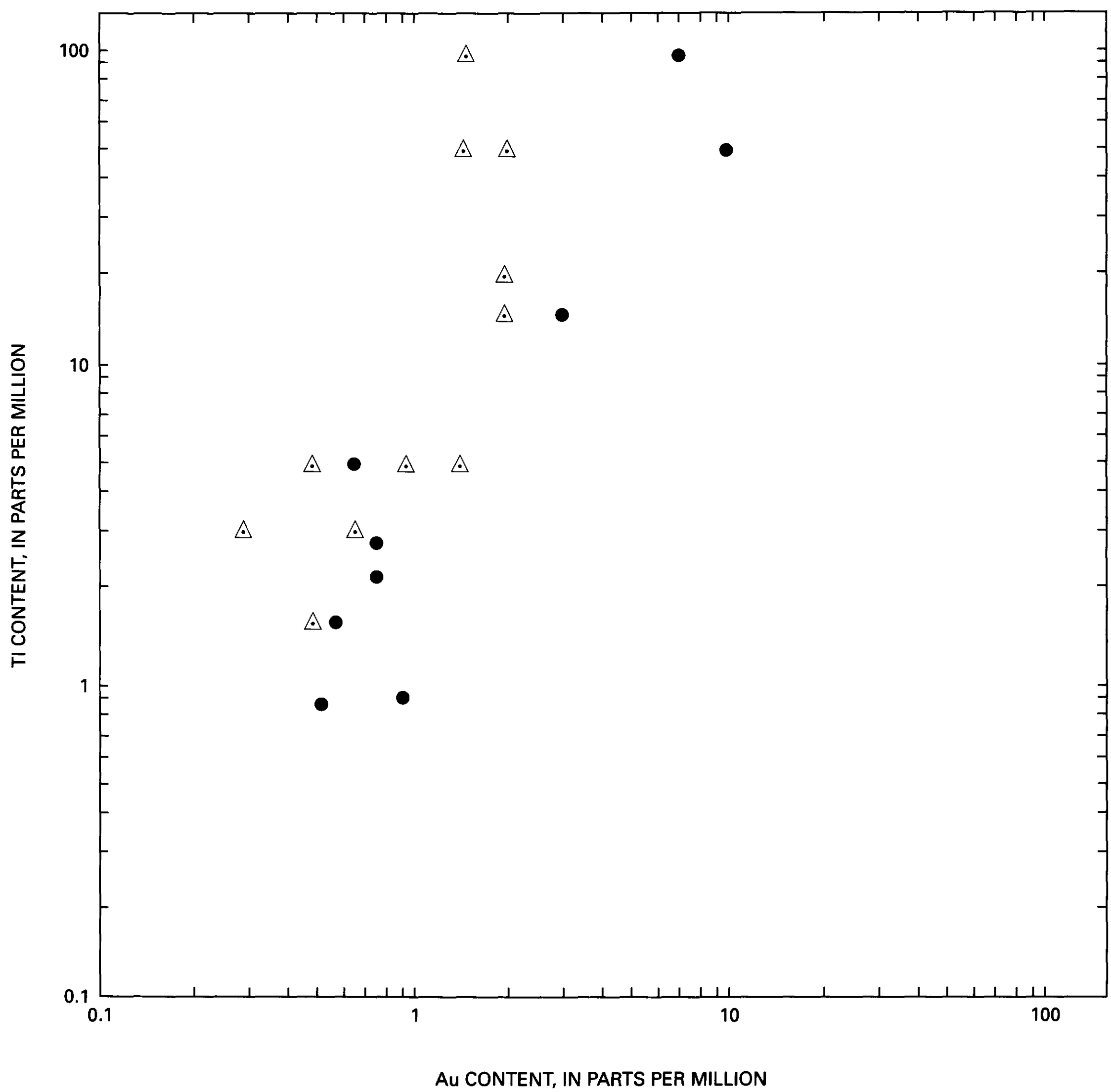


**Figure 6.** Thallium versus gold contents in samples from Yellowstone National Park (dots) and Steamboat Springs, Nev. (triangles), that contain at least 0.1 ppm Au.

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