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Active and fossil hydrothermal-convection systems of the Great Basin

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ABSTRACT

The Great Basin contains hundreds of active thermal spring systems, most discharge at temperatures much below boiling and generally lack characteristics likely to be preserved. Twenty-eight systems have measured or geochemically indicated subsurface temperatures from 150°C to 265°C.

The epithermal group of Au-Ag vein deposits of the Great Basin are the "fossil" equivalents of some active systems, including Steamboat Springs, Nev., and Broadlands, New Zealand, but other active systems of nearly equal temperature are not known to be depositing Au and Ag.

This paper compares the characteristics of the active and fossil epithermal vein systems, including their present distribution, physical and chemical characteristics, and evolution through space and time. The fossil systems ranged from ~0.2 to 7% salinity and averaged at least 1% (about twice the present systems).

Many epithermal Au-Ag deposits are also enriched in As, Sb, and Hg, and some contain Tl, Bi, Se, Te, and B. We are analyzing hot-spring sinters for these "mobile" elements as well as Au and Ag. Steamboat Springs is the only presently active Great Basin system whose sinters commonly exceed our detection limits of 0.1 ppm Au and Ag and also are highly enriched in most other mobile elements. Long Valley, Calif., is another possible example, but Roosevelt hot springs, a volcanic-centered system in the eastern Great Basin, is high in most of the mobile elements, but not in Ag and Au.

The "disseminated" or "sediment-hosted" gold deposits, from available data, are older than most epithermal veins. Carlin and Getchell(?) are enriched in the "mobile" element group, but our data are inadequate for a clear understanding of interrelations.

INTRODUCTION

Most known active hydrothermal convection systems discharge at the surface as hot springs. Some active systems are not discharging now but have discharged in the recent past, and others may never have discharged directly to the surface.

Fossil hydrothermal convection systems have probably been abundant through much of the Tertiary period, presumably varying greatly in number and intensity. Fossil low-temperature systems would leave little evidence of their former activity. High-temperature systems that altered the rocks along their channels, deposited metalliferous ores near these channels, or formed siliceous spring deposits where they discharged at the ground surface of the time are the fossil equivalents of some present-day high-temperature systems. This paper focusses on former systems that deposited ores generally known as epithermal gold-silver deposits. We compare the distributions, salinities, and temperatures of these two groups through study of the active systems and any available evidence on temperatures, salinities, and rare chemical elements of the fossil systems.

ACTIVE SYSTEMS

In a recent assessment of geothermal resources of the United States, 28 convection systems within or immediately adjacent to the Great Basin were identified as indicating reservoir temperatures of at least 150°C (Brook and others, 1979). In part, temperatures were physically measured in drilled wells, but in others, minimum temperatures were estimated from chemical geothermometers, with an uncertainty generally less than 10°C. Other high-temperature systems surely exist, either not discharging at the surface or mixing with normal ground water below the surface and not yet identified.

Table 1 lists the 28 identified systems, and figure 1 shows their locations. Most of these 28 high-temperature systems are clustered along or near the west boundary of the Great Basin and in the "Battle Mountain High" of above-normal conductive heat flow of northern Nevada (Muffler, 1979, pl. 1). The eight systems in table 1 that have indicated reservoir temperatures >200°C are identified by name in figure 1.

Three systems along the western margin of the Great Basin are associated with silicic volcanism younger than ~1 m.y., including Steamboat Springs, Nev., Long Valley, Calif., and Coso, Calif. Roosevelt Springs, Utah, is the only system near the east basin margin with similarly young volcanism; its reservoir temperature, near 265°C, is the highest yet identified in the Great Basin.

Four systems, Mickey, Oreg., and Humboldt House, Beowawe, and Desert Peak, Nev., have no

Table 1. Active geothermal systems of the Great Basin with measured or geochemically indicated temperatures >150°C[1]

State	Name	N. Lat		W. Long		No.[1]	Temp., °C[2]
CA	Surprise Valley	41	40.0	120	12.0	35	152
CA	Long Valley	37	40.0	118	52.0	56	227
CA	Coso	36	3.0	117	47.0	57	220
[3]CA	Randsburg	35	23.0	117	32.0	58	172
NV	Baltazor	41	55.3	118	42.6	130	158
NV	Pinto	41	21.0	118	47.0	132	173
NV	Gerlach	40	39.7	119	21.7	137	178
NV	San Emedio Desert	40	24.0	119	25.0	138	166
NV	Steamboat Springs	39	23.0	119	45.0	141	228
NV	Lee	39	12.6	118	43.4	143	166
[3]NV	Soda Lake	39	34.0	118	51.0	144	157
[3]NV	Stillwater	39	31.0	118	33.1	145	159
[3]NV	Fernley	39	35.9	119	6.4	146	182
NV	Brady	39	47.2	119	0.0	147	155
[3]NV	Desert Peak	39	45.0	118	57.0	148	221
NV	Humboldt House	40	32.1	118	16.1	151	217
NV	Kyle	40	24.4	117	52.9	152	159
NV	Leach	40	36.2	117	38.7	154	162
NV	Beowawe	40	34.2	116	34.8	162	229
NV	Hot Sulfur (Tusc.)	41	28.2	116	9.0	164	165
NV	Sulphur Hot Springs	40	35.2	115	17.1	169	178
OR	Crumps	42	13.8	119	53.0	190	167
OR	Mickey	42	40.5	118	20.7	196	205
OR	Alvord	42	32.6	118	31.6	197	181
OR	Hot Borax Lake	42	20.0	118	36.0	198	191
OR	Trout Creek	42	11.0	118	23.0	199	154
[3]UT	Cove Fort	38	36.0	112	33.0	208	167
UT	Roosevelt	38	30.0	112	50.9	209	265

[1] Identification number used by Brook and others, 1979.

[2] Estimated reservoir temperature; underlined systems exceed 200°C.

[3] No present surface discharge of water.

clear relations to young volcanism. Instead, they seem more closely related to high regional conductive heat flow.

Southern Nevada is notably lacking in high-temperature spring systems for reasons that are not yet clear. Their apparent absence may be related to the dry climate, low annual rainfall of the region, and no young silicic volcanism. In addition, many of the intermontane basins have deep water tables, with subsurface drainage through carbonate aquifers.

Low-temperature systems (<150°C) are not considered here because they seldom form sinter deposits, veins, or hydrothermal mineral associations likely to be preserved or recognized as fossil geothermal systems.

FOSSIL PRECIOUS METAL SYSTEMS OF THE GREAT BASIN

Most of the ore deposits called "epithermal" by Lindgren (1933 and earlier studies) consist of Au-Ag (or Ag-Au) veins in or closely associated with Tertiary volcanic rocks of the Great Basin, although he also included deposits mined primarily for Hg, Sb, and As. The first worker to concentrate on epithermal precious metal deposits was Nolan (1933), who focused on their physical characteristics, mineralogy, and great differences in Au/Ag ratios.

The most thorough recent review of precious-metal veins, largely or almost entirely in volcanic rocks of western U.S. and Mexico, was by Buchanan (1981), who objected to the term "epithermal" as a misnomer with respect to temperature. He also excluded similar veins entirely in non-volcanic rocks, as well as other precious metal deposits of recent interest, variously called "disseminated," "carbonate-hosted," "invisible gold," "bulk minable," and "Carlin type." The relations of most of these precious metal deposits to the classic volcanic-hosted veins are still being debated and are reviewed briefly here. Table 2 lists the available data on locations, ages, temperatures, and salinities of these systems, and figure 2 shows their distributions.

COMPARISON OF ACTIVE HIGH-TEMPERATURE CONVECTIO SYSTEMS WITH FOSSIL Au-Ag ORE DEPOSITS

Table 3 compares the active convection system with the fossil Au-Ag ore deposits of the Great

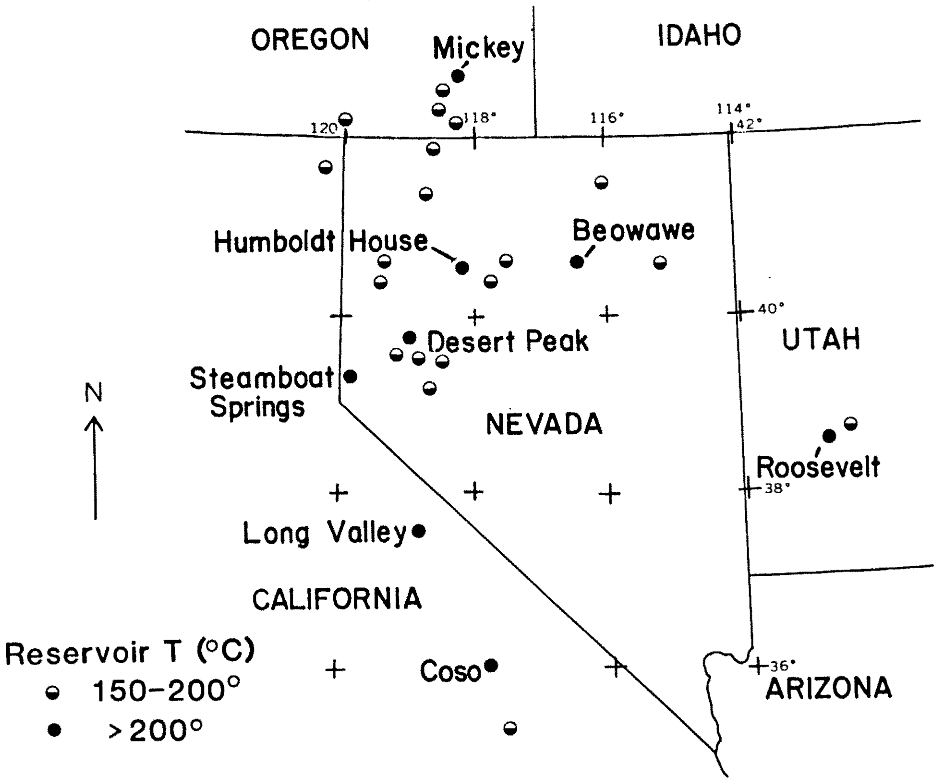

Figure 1. Active geothermal systems of the Great Basin, >150°C

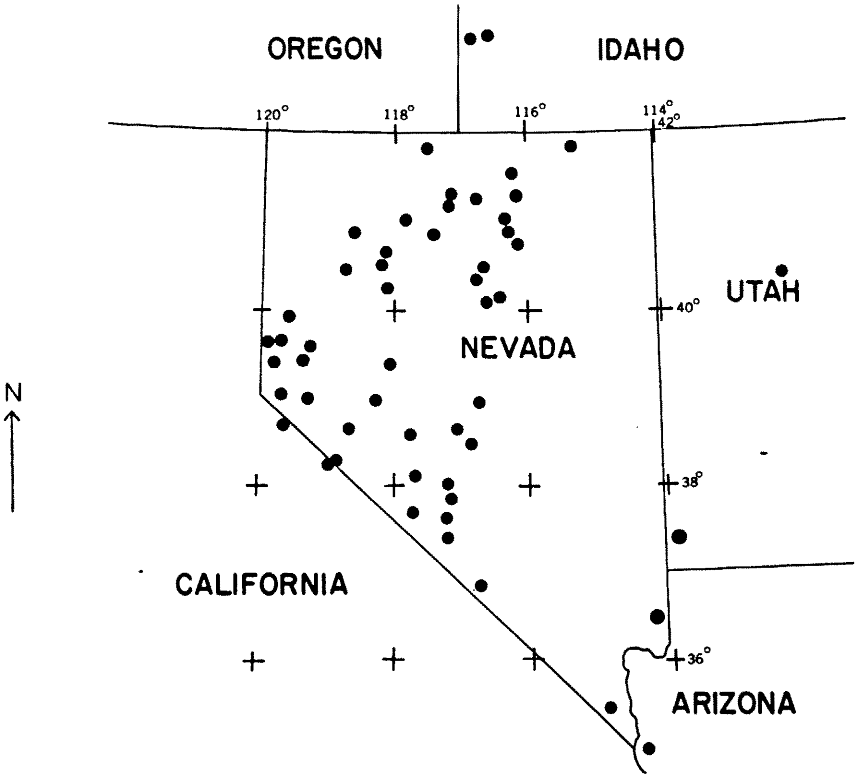

Figure 2. Gold-silver deposits of Nevada and nearby areas

Table 2. Gold-Silver deposits of Nevada and nearby areas, indicating ages, salinities, and temperatures of ore solutions.

State	No.	District	Lat.	Long.	Age, m.y.[1]	Salinity[2]	Temps, °C[3]	Refs[4]
NV	1	Adelaide	40 51	117 30	14			S
NV	2	Aurora	38 17	118 54	~11	0.2 - 1.7	227 - 255	S, N, Bu
[5]NV	3	Blue Star	40 54	116 19	37.5			B
[5]NV	4	Borealis	38 40	118 45	5			B
NV	5	Buckhorn	40 10	116 25	14.6			S, Bu
NV	6	Buckskin	38 59	119 20				B
NV	7	Bullfrog	36 55	116 48	9			S, Bu
[5]NV	8	Bullion	40 23	116 43	35			S
NV	9	Camp Douglas	38 21	118 12	15			S, G
[5]NV	10	Carlin	40 45	116 18	90		~150 - 200	N
NV	11	Cedar Mt. (Bell)	38 35	117 47		0.2 - 1.7	250	Bu
NV	12	Comstock Lode	39 03	119 37	~13		250 - 300	S, Bu
NV	13	Cornucopia	41 32	116 16	15			Bu
[5]NV	14	Cortez	40 08	116 37	35		~150 - 200	B, N, S
NV	15	Cuprite	37 31	117 13				A
NV	16	Divide	37 59	117 15	~16			S, Bu
[5]NV	17	Getchell	41 12	117 16	90			B
NV	18	Gilbert	38 09	117 40	8		275	Bu, S
[5]NV	19	Gold Acres	40 15	116 45	94	5.4 - 7.3	160 - 185	B, N
NV	20	Gold Circle	41 15	116 47	15		175 - 200	S, Bu
[5]NV	21	Gold Strike	40 59	116 22	78.4			B
NV	22	Goldfield	37 43	117 13	20		200 - 300	A, Bu, S
[5]NV	23	Hasbrouch	37 59	117 16	16			B
NV	24	Humboldt	40 36	118 11	73			Bu
NV	25	Jarbidge	41 52	115 26	14			S, Bu
NV	26	Manhattan	38 33	117 02	16	0.4 - 1.9	220	S, N
NV	27	National	41 50	117 35	15.5			Bu
[5]NV	28	Northumberland	38 57	116 47	84.6			B
NV	29	Peavine	39 36	119 55				A
[5]NV	30	Pinson	41 10	117 17	90?			B, S
NV	31	Pyramid	39 52	119 37	21			A
NV	32	Ramsey (Lyon)	39 27	119 19	10		221	S, Bu
NV	33	Rawhide	39 01	118 20	16			S, Bu
[5]NV	34	Rochester	40 17	118 09	58 - 79	~6	270 - 310	V, N
[5]NV	35	Round Mountain	38 42	117 04	25	0.2 - 1.4	250 - 260	B, N, S
NV	36	Searchlight	35 27	114 55				Bu
NV	37	Seven Troughs	40 29	118 46	14		240 - 318	S
NV	38	Silver Dike	38 19	118 12	17.3		300	S, G
NV	39	Silver Peak	37 47	117 43	5			S, Bu
[5]NV	40	Standard	40 31	118 12	73			B
NV	41	Steamboat Springs	39 23	119 45	<3	0.2	(90) - 230	S
NV	42	Sulphur	40 53	118 40	1.9			A
[5]NV	43	Talapoosa	39 27	119 19	10			S
NV	44	Tenmile	41 02	117 53	16	0.4 - 7.3	(135) - 330	N, S
NV	45	Tonopah	38 04	117 14	19	<1	240 - 265	S, Bu
NV	46	Tuscarora	41 17	116 14	38			S, Bu
NV	47	Widekind	39 35	119 45				A
NV	48	Wonder	39 24	118 06	22			S, Bu
CA	1	Bodie	38 12	119 00	7		215 - 245	S
CA	2	Monitor	38 42	119 40	5			S
AZ	1	Oatman	35 02	114 23			220	Bu
ID	1	DeLamar	43 02	116 50				Bu
ID	2	Silver City	43 02	116 44	~15			Bu
[5]UT	1	Gold Strike	37 23	113 53	78.4			Bu
[5]UT	2	Mercur	40 19	112 12				Bu

[1] Age, in millions of years; ~ indicates approximate average of range. Adularia most common mineral dated; see Silberman et al., 1976, and Buchanan, 1981, for summaries of minerals and dates.

[2] Salinity, from freezing-point depression of fluid inclusions, in NaCl equivalent.

[3] Temperatures of homogenization of fluid inclusions, with no pressure correction; probably valid for most of these deposits (Buchanan, 1981).

[4] References: S (Silberman and others, 1976, 1979); B (Bonham, 1982); Bu (Buchanan, 1981); A (Roger Ashley, personal communication, 1983); N (Nash, 1972); V (Vikre, 1981); G (Garside, 1979); and W (Andrew Wallace, personal communication, 1983).

[5] Deposits variously called disseminated, carbonate-hosted, Carlin-type, bulk mining, or invisible gold, and differing from classic epithermal veins; many other similar deposits recently discovered but no age or fluid-inclusion data available. The Rochester district has characteristics of both types.

Table 3. Active high-temperature convection systems compared with "fossil" Au-Ag ore deposits

	Active systems[1]	"Fossil" Au-Ag ore systems[2]
Temperature range, °C	150-265	~130-330
Surface Discharge	Most but not all	Some; evidence generally lacking
Sinter deposited from surface springs	Many; can be intermittent	A few; evidence generally lacking
Typical dissolved matter in fluids, %	0.1 to 0.8	0.2 to > 3
Water composition	Na-K-Cl-HCO_3	? - Mainly Na-Cl
Origin of water	Dominantly meteoric[3]	Dominantly meteoric[3]
Water pressure	Near hydrostatic for depth & T's	Near hydrostatic?
Evidence for boiling	Upper parts of most discharging systems[4]	Upper parts of most most systems[5]
Post-sinter erosion	0 to few 10's of m	Generally unknown
Source of energy	Volcanic-centered + high regional heat flow	Volcanic-centered?
Host rocks	Mainly alluvium near surface; variety of igneous, sedimentary, and metamorphic rocks at depth	Mainly volcanic rocks, in part underlain by sedimentary and metamorphic rocks
Open-space depositional banding	Some, but rarely studied (generally no core	Prevalent in most
Ore minerals		
Au	Unknown; Au low in most?	Au, electrum, selenides, tellurides[5]
Ag	Unknown (some pyrargyrite)[6]	Argentite, electrum, various sulfosalts[5]
Au-Ag distribution with depth	Au and Au/Ag decrease downward[7]	Au and Au/Ag decrease downward, generally with increasing base metals[5]
Maximum depth range of ore	Not well defined	Au-Ag ore generally < 350 m; related to initial boiling?[5]
Hydrothermal gangue		
SiO_2 near surface	Opal, crystobalite	Chalcedony
SiO_2 at depth	Chalcedony, quartz	Chalcedony, quartz
Feldspars	Nearly pure K-spar[6] in upper part; some deeper albite	Nearly pure K-spar[6], some deeper albite
Carbonates	Calcite, in part lamellar, overgrown by quartz, partly dissolved	Calcite commonly overgrown by quartz, then partly dissolved
Sulfides	Pyrite, stibnite, cinnabar, rarely marcasite; arsenopyrite, base metals at depth	Pyrite, other sulfides (Buchanan, 1981)
Alteration minerals	Fn.gr. micas, clays; propylitic zoning; kaolinite, alunite, opal near and above water table	Similar to active systems (Buchanan, 1981)
Depth zoning of rare elements	Au, Hg, B, Tl, As, Sb enriched upwards; Ag/Au, Cu, Pb, Zn may increase downward	Au, Hg, Sb, commonly enriched upward; Ag/Au and base metals increase downward (Buchanan, 1981)
Ratio, vein length/depth	?	Commonly 2/1 or greater[5]

[1] Restricted to systems of at least 150°C, either by direct measurements or chemical geothermometry.

[2] Dominantly the classic "bonanza" veins in volcanic rocks, excluding the disseminated or carbonate-hosted deposits of Table 2.

[3] Most active and fossil systems of Great Basin are dominantly meteoric water (O'Neal and Silberman, 1974; White, 1974).

[4] Direct measurement; monoclinic, nearly pure K-feldspar (adularia) and tabular vein calcite crystals, commonly with quartz overgrowths.

[5] (Buchanan, 1981); the best evidence for boiling is associated vapor-rich and liquid-rich fluid inclusions, vein calcite, and adularia.

[6] At Steamboat Springs, uncertain elsewhere.

[7] Au and Ag decrease downward as base metals increase at Steamboat Springs, NV, Broadlands, N.Z., and Waiotapu, N.Z., but data not available for most systems.

Basin. These fossil systems are dominantly the classic "bonanza" veins in volcanic rocks, excluding the disseminated or carbonate-hosted deposits of table 2, discussed below.

TEMPERATURES

The active systems (excluding all systems below 150°C) range as high as ~265°C (Roosevelt, Utah). In contrast, most ore deposits with temperatures of deposition determined from fluid inclusions (Table 2) range from 200° to 300°C, with an extreme range of 150°C (excluding Steamboat Springs and post-gold calcite inclusions from Tenmile) to 330°C in two of the tabulated deposits, with no data available from the others. Average temperatures of the studied deposits are close to 250°C. For comparison, temperatures of deposition of only 3 of the disseminated deposits are available: Carlin, 150° to 200°C (Nash, 1972); Gold Acres, 160° to 185°C (Nash, 1972); and Rochester, 270° to 310°C (Vikre, 1981, which has characteristics of both ore types).

SURFACE DISCHARGE

Most active geothermal systems discovered to date in the Great Basin discharge at the surface. Six systems of Table 1 have had no recent discharge, including Coso, Calif. (formerly discharge but now vents only gas); Lee and Brady, Nev. (discharge at very low rates as compared to former rate); and Roosevelt, Utah, which decreased to a seeping discharge of high-silica water by 1957 but self-sealed its vent with amorphous SiO_2 about 1960. Many of these spring systems discharged at much higher rates and temperatures in the past, probably during the late Pleistocene when water supply was abundant and water tables intersected the ground surface. The fossil precious-metal systems generally provide no direct evidence for discharging on the ground surface of the time. True sinter provides the most conclusive evidence but, if present over these fossil systems, it has generally been eroded. At least 17 of the active systems of Table 1 deposited sinter at some time in their past, thereby providing evidence for discharge temperatures close to boiling, and subsurface reservoir temperatures near or above 180°C (White, 1973).

SALINITIES ANE WATER COMPOSITIONS

Most active systems of the Great Basin have low contents of dissolved matter, generally ranging from <0.1 to 0.25 weight percent. However, a few systems listed in Table 1 range as high as 0.8 percent (Desert Peak, Nev., and Roosevelt, Utah), and Gerlach and Stillwater have intermediate salinities. Dissolved matter of most high ~~temperature springs is dominated by NaCl and~~ bicarbonate. Beowawe, however, is unusual for its low content of dissolved solids (~0.1 percent), containing only ~50 ppm Cl but considerably higher total carbonate and bicarbonate (generally near 400 ppm; Garside and Schilling, 1979).

In comparison, the epithermal vein fluids ranged from ~0.2 to 7.3 percent in salinity (NaCl equivalent from freezing-point depression of fluid inclusions), with most ranging from 0.2 to percent. No data exist on actual compositions of these fluids. Ore-fluid salinities are seldom given the attention that Nash (1972) gave to the Tenmile district, where most inclusions indicate 0.9 to 2.1 weight percent, but late quartz fluids of two mines indicate ~7 percent, and a late (later?) calcite only 0.4 percent. The available data indicate that the fluids of epithermal veins are nearly always more saline than active high-temperature hot springs. Ore fluid salinities of the disseminated deposits are even less well know because of the scarcity of satisfactory fluid inclusions. Only the data from Gold Acres are "fairly satisfactory," according to Nash (1972), as judged from fluid proportions in tiny inclusions from Carlin and Cortez that seemed to homogenize at 175 ± 25°. No inclusions were suitable for freezing-stage salinities.

ORIGIN OF WATER

Water of the active systems is entirely or dominantly meteoric (Craig and others, 1956), as indicated mainly by the hydrogen isotopes of water. Volcanic-centered systems are suspected o having some magmatic water (in or from molten magma), but much of this water may ultimately hav been meteoric, evolved connate, or metamorphic rather than derived from the mantle. A few thermal springs in California (White and others, 1973) are now known to contain a significant proportion of evolved connate or metamorphic water, based on contrasts in their δD values relative to present meteoric waters.

Fluid inclusion waters of fossil epithermal systems are also dominantly meteoric (O'Neil and Silberman, 1974), although climatic and elevation differences since formation of the ore deposits account for some of the contrast with present meteoric waters. The only epithermal district these authors suspected of having a significant direct magmatic content was the Comstock Lode, where one high-grade ore sample differed by ~50°/₀₀ in δD from present meteoric waters of the area. More extensive systematic study of other epithermal districts will be required to determine the possible relations of the δD values of individual districts with depositional age and fluid inclusions. Multiple analyses from each district are necessary to establish whether other types of water than meteoric are present, but the considerably higher salinities of most inclusion fluids, relative to the dilute active systems, favor the possibility of detecting other origins.

WATER PRESSURES AND EVIDENCE FOR BOILING

~~Temperatures and depths in the active~~ high-temperature systems indicate that their uppe parts are generally adjusted to the hydrostatic boiling-point curve (White, 1968). A few systems need a small correction for high salinity or hig gas content. At greater depths in most systems, pressure is sufficiently great to prevent boiling or the separation of a vapor phase if gas contents are high. Steamboat Springs (White, 1968) initially had pressures slightly above hydrostatic in several drill holes, but no special attention was given to the phenomenon. Later research drilling in Yellowstone Park (White and others, 1975) established the existence of overpressures locally as much as ~30% above hydrostatic because of high silica contents and impeded flow (self-sealing) of the upflowing water. Careful measurements at Beowawe, Nev., and Roosevelt, Utah, before their disturbance by geothermal exploration, probably would have identified overpressures in these systems.

Fluid-inclusion studies of some epithermal veins indicate two populations of coexisting inclusions: One set homogenizes to liquid with increasing temperature while the second set homogenizes to vapor (or largely vapor). This result is interpreted as due to boiling, with individual inclusions trapping different proportions of vapor and liquid in a boiling system. Boiling can alternate with non-boiling through time as a system becomes self-sealed, overpressure develops as the cold, more dense recharge part of the system becomes effective in response to decreasing flow rates; hydrofracturing may eventually relieve the overpressure.

POST-SINTER EROSION

Erosion of the active systems is generally slight, ranging from essentially 0 to at least a few tens of meters at Steamboat Springs (White and others, 1964) and probably lesser amounts in younger systems. Most epithermal systems have been eroded so extensively that no direct evidence of sinter deposition is preserved, and precise estimates of the extent of erosion generally cannot be made. Critical evidence can be provided from preserved sinter and evidence of fossil water-table relations. Both kinds of evidence require careful identification and correlation with the ore deposit. Of the deposits listed in Table 2, sinter is stated to exist near the Aurora, Nev., and Bodie, Calif., systems (M. L. Silberman and F. J. Kleinhampl, oral commun.); Borealis, Nev. (Don Strachan, oral commun.); DeLamar, Idaho (Pansze, 1975); Silver City, Idaho (Dan Shawe, oral commun., 1981); Divide and Sulphur, Nev. (Andrew Wallace, oral commun., 1981); and Steamboat Springs, Nev. (White and others, 1964). We have examined some of these deposits and consider them to be chalcedonic sinter, initially deposited as opaline sinter but, after burial, later chalcedonized with time and higher temperatures. The different characteristics of various types of sinter were described by White and others (1968). Previously existing rocks are also commonly converted into sinterlike rocks through acid leaching and chalcedonization related to boiling from a subsurface water table; some mercury deposits of the "opalite" type in Nevada (Bailey and Phoenix, 1944) are of this origin. All claimed sinters need to be restudied in the light of petrographic, chemical, and field characteristics; we are reluctant to identify several doubtful sinters until such studies are made.

SOURCES OF ENERGY

Of the active convection systems of Table 1, Long Valley, Coso, Steamboat Springs, Soda Lake, and Roosevelt are closely associated with volcanic systems about 1 m.y. old or less. Volcanic heat is viewed as the major source of their energy with the possible exception of Soda Lake (near a young basaltic cinder cone in a region of high conductive heat flow).

However, the energy source for most of the other active systems listed in table 1 is less certain. Most of these are in or near the "Battle Mountain heat-flow high," where conductive heat flow is at least 50 percent above the continental average, but silicic volcanic rocks younger than 10 m.y. are absent (Lachenbruch and Sass, 1977).

Much recent interest has focused on the abundance of the helium isotopes ^{3}He and ^{4}He. ^{3}He significantly above atmospheric is now generally viewed as indicating a mantle or primitive constituent, in contrast to ^{4}He, which forms mainly in the earth's crust from radiogenic reactions of U and Th. ^{3}He/^{4}He ratios 4 to 16 times above atmospheric have been identified along oceanic spreading ridges, in Iceland, Yellowstone Park, Lassen Volcanic National Park, Steamboat Springs, Nev., and in many other volcanic areas. In contrast, Beowawe, Nev., and other systems driven by high conductive heat flow have only ~10 percent of the atmospheric ratio, a value indicating a dominantly crustal heat source (which could also be old degassed magma bodies, as favored by Lachenbruch and Sass, 1977). Systematic study of the helium ratios of all high temperature spring systems of the Great Basin is urgently needed for a better understanding of present-day heat sources.

Many of the fossil epithermal systems listed in table 2 are closely related in space and time to contemporaneous active volcanism (Silberman, and others, 1976). Were all of these convection systems as closely related to volcanism as present-day Yellowstone and Steamboat Springs? Were there any epithermal ore-generating systems like present-day Beowawe, where subsurface temperatures are within the epithermal precious-metal range but the energy is supplied by crustal conductive heat?

HOST ROCKS

The host rocks of the active systems include varieties of igneous and sedimentary rocks, some of which are old igneous and metamorphic rocks unrelated to the present convection systems. The fossil ore systems also include a wide variety of associated rocks but are mainly near-surface Tertiary volcanic rocks not differing greatly in age from that of the mineralization (Buchanan, 1981); many of these volcanic rocks are underlain by sedimentary and metamorphic rocks. The main heat sources must normally be at least several thousand meters below the surface to account for the high hydrostatic pressures and temperatures required by the data of Table 2. Thus, the composition of the host rocks immediately adjacent to ore bodies can be largely coincidental.

OPEN-SPACE DEPOSITIONAL BANDING OF VEINS

One of the most characteristic features of epithermal veins is banded open space fillings from the vein walls inward; one wall is commonly almost a mirror image of the other; paired zones of inward-facing euhedral crystals are also very common. Characteristic shattering and brecciation indicate intermittent growth, perhaps with alternate filling or "self sealing," followed by renewed reopening and further separation of the walls, probably commonly by hydrofracturing but with tectonic fracturing also involved. Lindgren (1933, and his earlier reports on individual districts) was one of the first to recognize these features as indicative of low pressure and shallow depth. This concept is still generally supported, although most present-day economic geologists no longer agree that the concept of low temperatures is valid. The tectonic style is also consistent with crustal extension.

Banded or crustified veins also characterize the few active geothermal systems that have been core-drilled and studied systematically. Many examples of banding or crustification were observed in core from Steamboat Springs, Nev. (White, 1968), and in Yellowstone Park (Keith and others, 1978). Selected intervals of drill holes cored in New Zealand yielded some similar growth-banded veins. In commercial geothermal drilling, however, rock bits are normally used, with consequent loss of detailed vein characteristics.

ORE MINERALS

No gold mineral has yet been identified in the active systems, although black siliceous muds at Steamboat Springs contain as much as 15 ppm Au, and orange amorphous metastibnite as much as 60 ppm Au (White, 1981). Au and some other elements may be adsorbed on amorphous silica and fine-grained sulfides. In contrast, Au occurs in a various minerals in epithermal vein deposits but is "invisible" (adsorbed?) on carbon and other minerals of disseminated deposits.

The silver minerals deposited in active systems are also generally unknown, except that pyrargyrite has been positively identified in core from Steamboat Springs (White, 1981). A silver telluride was identified in tiny inclusions in sphalerite from Broadland, New Zealand, and both Au and Ag were much enriched in surface-deposited metastibnite. Both Au and the ratio Au/Ag decrease markedly downward in the three active systems most thoroughly studied (Steamboat Springs, Nev., and Broadlands and Waiotapu, New Zealand), both Au as Ag and the base metals increase.

A similar zonation of decreasing Au and Au/Ag with depth as base metals increase clearly occurs in most epithermal ore deposits (Buchanan, 1981). ~~The few exceptions are generally Au-rich and~~ acidic, in contrast to most vein deposits, where Ag generally dominates greatly over Au (by weight).

MAXIMUM DEPTH RANGE OF ORE

A significant aspect of most epithermal ore deposits is their abrupt termination of commercial ore with depth ("flat bottoming"), especially as indicated by the ore stopes. This observation is generally viewed as due to decreasing Au content, a less abrupt but effective decrease in Ag, and increasing base metals. The depth of bottoming is seldom >350 m below the surface, although mining in a few districts extends below 1000 m or more (Buchanan, 1981), commonly because Ag continues downward as base metals increase sufficiently to constitute minable grades. In a few epithermal districts, ore shoots are described as also terminating abruptly upward. Veins and vein structures, in contrast to ore grade, commonly extend both upward (where preserved) and downward beyond commercial grades.

Much less is known about the distribution of Au and Ag in the few active systems enriched in precious metals. These systems are never mined for their precious metals but have been explored principally for geothermal energy, so continuity or grade of precious metal "ores" has received little attention.

RATIOS OF VEIN LENGTH TO DEPTH

Buchanan (1981) tabulated the ratios of vein length to depth, based on stope dimensions rather than ore grade. In contrast to many other kinds of hydrothermal ore deposits, vein length commonly exceeds depth by a factor of at least 2. Erosion of the upper parts of some veins accounts in part for these ratios, but rather abrupt downward termination of the mining grade of ore (even though the veins continue downward) is viewed as the dominant factor.

Buchanan (1981) and others have suspected a chemical control over downward terminations, probably because of changes in the ore fluids, especially resulting from boiling. With upward flow, hydrostatic pressure decreases, the fluid start to boil, and CO_2 and H_2S are selectively lost to the vapor phase, thereby causing instability in the ore metal complexes. Buchanan (1981) concluded that evidence of boiling, especially from coexisting vapor-rich and liquid-rich fluid inclusions, commonly starts near the bottom of ore stopes. For further support, more systematic observations of the distribution of vein adularia, and calcite (especially the lamellar variety, overgrown with quartz) are needed for correlation, as Browne and Ellis (1970) did for the Broadlands system in New Zealand. These minerals are likely to correlate with boiling, loss of CO_2, and consequent increase in pH of the liquid.

Geothermal veins and vein structures in active systems have not yet been studied systematically with respect to the distribution of Au, and so the ratios of individual vein lengths to depths are not yet known. The permeability of vein ~~structures is significant~~ to the geothermal industry, indicating permeable aquifers likely to yield high flows of thermal fluids. Vein adularia has long been considered as a favorable indicator of permeable fluid channels (Browne and Ellis, 1970), unless these channels are later filled by self-sealing.

OTHER COMPARISONS OF ACTIVE AND FOSSIL SYSTEMS

Table 3 also compares other important characteristics of active and fossil convection systems that are adequately summarized by Buchanan (1981) for the epithermal volcanic-hosted vein systems, and summarized in Table 3 for the active systems.

MINOR ELEMENTS AS POSSIBLE INDICATORS OF INTERRELATED PRECIOUS-METAL ORE DEPOSITS

For many years we have been interested in a group of minor elements that may be significant in interrelating high-temperature hot springs, epithermal Au-Ag vein deposits, and, more recently, the disseminated or Carlin-type gold deposits. The association of Ag, Au, As, Sb, and Hg at Steamboat Springs has been known for many years (Lindgren, 1933; White and others, 1964; White, 1981). As, Sb, and Hg are associated with many epithermal veins (emphasized by Nolan, 1933), and Radtke and others (1972) demonstrated that As, Sb, Hg and Tl are characteristic of the disseminated gold deposit of Carlin, Nev., where the gold was invisible. As, Sb, and Hg were already known as sulfide minerals in the somewhat similar Getchell deposit, but little attention was given to the rare element Tl until its abundance and new thallium minerals were identified at Carlin (Radtke and others, 1972). Detailed study of the distribution of these trace elements was limited in part because their detection limits by ordinary emission spectrographic methods were appreciably higher than crustal abundances levels. Chris Heropoulos, in collaboration with Radtke and others, 1972; Heropoulos and others, in press), had initialed the development of new sensitive spectrographic methods, concentrating on the short-wave length radiation area of the spectrum, which is not normally utilized. As a consequence, detection limits for most volatile elements of this group in hot spring systems are now near or below the crustal abundances (Table 4). Elements not yet detected by these methods at average crustal abundance levels are Ag, Au, and Hg (close for all except Hg, but Hg is generally much enriched in near-surface materials). Bi, Se, and Te are also members of this group of volatile elements; however, their sensitivity is not high enough to make them detectable at the crustal abundance levels.

Hot spring sinters were selected as appropriate material for comparison because all true sinters were deposited at the ground surface from near-boiling springs discharging from reservoirs near or above 180°C. Uncertainties for each system are the actual discharge rate and reservoir temperature at the time of deposition of each sample, and post-depositional changes (diagenetic) after each sinter was first deposited. Chalcedonization of amorphous opaline sinter, generally through an intermediate cristobalitic stage (White and others, 1964), probably decreases the metal contents by remobilizing elements adsorbed on amorphous opal.

Table 4 summarizes our first reconnaissance effort to compare the active high-temperature systems of the Great Basin. None of the sinter samples was collected specifically for this purpose, and so the selected samples are not necessarily representative; only 7 of the 15 systems are represented by two or more samples, and only those systems with four or more analyses seem likely to approximate a representative spread of elemental contents.

Steamboat Springs is the only system of the group that is generally enriched in all elements, commonly by a factor of 10 or more. Au is strongly enriched above its crustal abundance to depths of ~70 m, but is below the limit of detection at greater depths (White, 1981, Table 2). Near-surface enrichments of As, Sb, and Hg are especially notable; the abundances of most of these elements decrease significantly with depth except Ag, which is 0.2 to 2 ppm in sinters to 25-m depth but is more strongly enriched in chalcedony-quartz-calcite veins to the greatest depth (136 m).

Most samples from Steamboat Springs are strikingly enriched above crustal abundances in Sb and As and generally much enriched in Hg, B, and Tl. In contrast, Zn, representative of near-surface base-metal concentrations, is always within detection limits but much below its crustal abundance.

Of all other active systems listed in Table 4, none shows much evidence for generating an epithermal ore deposit. Long Valley caldera, Calif., probably has the best possibilities: two of four samples contain detectable Ag (0.3 and 10 ppm), but Au was detected in only one (1.0 ppm); Sb, As, Hg, and B are strongly enriched, but Tl is low. Long Valley waters have undergone much near-surface dilution, so ores could be forming below the surface in the dilution zone.

Beowawe sinters are generally low in Ag, and only one of the four samples contains detected Au (0.2 ppm). As, Sb, Hg, and B are modestly enriched in some of these samples, but the general contents are modest in comparison with Long Valley and, especially, Steamboat Springs.

The major surprise of Table 4, at least for us, is the Roosevelt system, Utah, which has the highest salinity and temperature of those systems closely associated with young silicic volcanism. We had suspected that the minor elements would show close ties to epithermal Au-Ag ore deposits. Of seven Roosevelt sinter samples, most are approximately equivalent to Steamboat Springs in As, Sb, and B; Tl is higher, but Hg is lower. However, the sinters are almost lacking in precious metals: only one of the seven samples contained detectable Ag and none contained detected Au. Therefore, Roosevelt is a "bust" as far as Au and Ag contents of sinters are concerned! However, this is the only system containing notable Zn, with two of the seven samples (70 and 300 ppm) equaling or exceeding the crustal average.

TIME-SPACE RELATIONS OF THE EPITHERMAL VEINS

Au-Ag deposits of Nevada and adjacent areas occur mainly in a broad north-northeast striking belt through west-central Nevada (fig. 2).

Table 4. "Volatile" elements and their concentration ranges in ppm in Hot Spring Sinters[1] as compared to crustal abundances

Locality	Temp.[2]	No. of Samples	Ag 0.07[3]	Au <0.05[3]	As 1.8	Sb 0.2	Tl 0.45	Hg 0.08	B 10	Zn 70
Nevada										
Steamboat Springs	228	10	2(<0.1) 6(0.1-1.0) 5.0,15	6(<0.1) 4(0.2-1.5)	6(2.0-70) 4(100-700)	3(70-300) 7(700->2000)	3(<1.0) 5(1.5-7.0) 2(70)	1(<1.0) 6(1.0-30) 3(1000->2000)	5(20-70) 5(200-1000)	5(0.5-2.0) 5(5.0-10)
Beowawe Geysers	229	4	1(<0.1) 3(0.5-1.0)	3(<0.1) 0.2	4(5.0-10)	3(20) 5.0	2(<1.0) 1.0,2.0	4(2.0-10)	4(70-200)	2.0,3.0 10,30
Pinto	173	3	2(<0.1) 0.3	3(<0.1)	10,30,100	20,30,30	2(<1.0) 7.0	20,300,1000	30,150,300	1.0,2.0,10
Brady	155	2	2(0.5)	2(<0.1)	20,30	30,50	2(<1.0)	20,20	300,300	10,15
Leach	162	1	7.0	<0.1	20	20	<1.0	1.5	150	15
Gerlach	178	1	1.5	<0.1	30	10	1.0	5.0	1500	50
Baltazor	158	1	<0.1	<0.1	20	15	<1.0	<1.0	300	20
Howard	?[4]	1	<0.1	<0.1	30	30	<1.0	50	30	<1.0
Jersey Valley	?[4]	1	<0.1	<0.1	15	10	<1.0	5.0	70	3
Lee	166	1	0.3	<0.1	20	30	1.5	5.0	200	15
California										
Long Valley	227	4	2(<0.1) 0.3,10	3(<0.1) 1.0	3(50)	3(200-300) 100	3(<1.0) 30	2.0,5.0 2.0	30,100 50,700	4(10-20) 700,1000
Coso	220	2	<0.1	<0.1	7.0,20	100,200	<1.0	20,50	200	<1.0,7.0
Surprise Valley	152	1	<0.1	<0.1	20	20	<1.0	50	100	3.0
Oregon										
Mickey	205	1	<0.1	<0.1	70	50	<1.0	50	1500	5.0
Utah										
Roosevelt	265	7	6(<0.1) 0.5	7(<0.1)	5(5.0-20) 100,300	3(30-100) 3(200) 2000	5(1.0-5.0) 50,150	4(1.0) 3(2.0-20)	6(200-1000) 50	1(<1.0) 4(2.0-20) 70,300

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[1] The short wavelength radiation (SWR) method (Heropoulos, et al, in press) was used to determine concentrations and to establish limits of detection.

[2] Temperatures measured in drill holes or indicated by chemical geothermometry (Brook, Mariner, and others, 1979)

[3] Crustal abundance of each element in ppm from Krauskopf (1967).

[4] Discharge too low for chemical geothermometry

Northwestern and southeastern Nevada are almost barren of these deposits. The most favorable terrane, as presently known, terminates southwestward near the Nevada-California stateline (close to the Walker Lane), and abruptly southeastward; the northwest boundary is equally abrupt.

In a broad way, mid-Tertiary volcanism started in northeastern Nevada, expanded in a crudely arcuate form (Stewart and others, 1977) to the south and west through time, finally leaving most of Nevada barren of volcanism during the last 6 m.y. (except for local basalt).

Epithermal vein mineralization, as evaluated from the limited data in table 2, broadly followed the same migrating arcuate system except for greater irregularity and shorter, sharper ore-depositing pulses (Silberman and McKee, 1974). All four dated ore systems of the oldest mid-Tertiary volcanic group (43 to 34 m.y.; Stewart and others, 1977) range in age from 38 to 35 m.y. The second mid-Tertiary volcanic group (34 to 17 m.y.) has five associated dated ore systems, all of which, if representative, formed within a short period of 25 to 19 m.y. B.P. These deposits, for unknown reasons, are concentrated only in the southwestern part of the corresponding volcanic belt, approximately parallel to the Walker Lane. A total of 15 districts indicate a sharp climax in epithermal mineralization within the brief timespan of 3 m.y. from 17 to 14 m.y. B.P. (the older portion of Stewart's 17 to 6 m.y. volcanic group), and are distributed rather uniformly over most of the broad northeast-striking belt shown in Figure 2. During the later part of this volcanic period (<14 to 6 m.y. B.P.), mineralization waned; the six dated districts range in age from 7 to 13 m.y.; their locus shifted southward, being restricted to a northwest-striking belt adjacent to the Walker Lane (near the California-Nevada stateline).

The youngest ore group, 0 to 6 m.y. B.P., includes three districts ~5 m.y. old that continue the Walker Lane trend, followed by two young hot-spring systems. The Sulphur system, adjacent to the Black Rock Desert (1.9 m.y. old from dating of alunite, according to Andrew Wallace (oral commun., 1981), has a superb fossil sinter system, reportedly underlain by ore just east of Sulphur Station, where warm gases, H_2S, and elemental S indicate continuing activity after the dated alunite. Steamboat Springs has been discussed above; its activity started prior to a well-dated basaltic andesite flow (2.5 m.y.) and still continues (Silberman and others, 1979). The high metal contents of present-day Steamboat fluids prove that metal transport and ore generation was not restricted to early activity but is still continuing. Together, the activity at Steamboat Springs and Sulphur suggest either a new northeastward trend or the northeastern limb of a westward-advancing arc, depending on whether Long Valley is indeed a young active epithermal Au-Ag system.

DISSEMINATED DEPOSITS

Interrelations between the middle- and late-Cenozoic epithermal vein systems and the pre-Tertiary sediment-hosted "disseminated" deposits are still not clearly understood. Meager data on enrichment of the minor elements As, Sb, Tl, Hg, and B at Carlin and probably also at Getchell suggest a close similarity to the active epithermal vein systems of Steamboat Springs and Broadlands, New Zealand. We had suspected that these minor elements might establish a common tie between all epithermal veins, the active high-temperature spring systems, and the disseminated group, and that the principal difference would be the nature of the host rocks. However, the data on these systems listed in table 2, if representative, suggest that the disseminated group is generally older. Highly inadequate fluid inclusion data also suggest that temperatures may have been slightly lower and the salinity of ore fluids higher than the mid-Tertiary and younger epithermal veins. Rochester may be a special exception in being older than most epithermal veins but having the same general temperature range and Ag enrichment appropriate for most of these veins (Vikre, 1981). However, Rochester fluid inclusions also have unusually high salinity, perhaps more appropriate for the disseminated group.

Systematic study of the distribution of As, Sb, Tl, Hg, and B is needed for all active and fossil ore systems. These minor elements are strongly zoned with depth in the active Steamboat and Broadlands systems, which are "open" and may be dispersing most of these minor elements near the surface by means of discharging springs. These elements decrease rapidly downward in abundance at Steamboat Springs (White, 1981), where cinnabar was identified to a maximum depth of only 15 m below the present surface in eight drill holes, and stibnite only to 45 m. Although distinct As, Tl, and B minerals have not been identified at Steamboat, the abundances of these elements decrease rapidly to ~25 m and are lower (close to the system's background) at greater depths (White, 1981), wherever temperatures exceed ~140°C. In contrast, these elements were concentrated in ores yielding fluid-inclusion temperatures of 150° to 200°C in the Carlin deposit (Nash, 1972) and presumably at similar temperatures at Getchell. These relations suggest that Carlin, Getchell, and, possibly, the other pre-Tertiary disseminated gold deposits differ from epithermal veins not only in age but also in structural, chemical, and other depositional controls. The fluids may have been entrapped below a permeability barrier where they could not discharge directly to the surface but were cooled by conduction, and eventually mixed with other pore fluids below the surface.

CONCLUSIONS

Among the active high temperature convection systems of the Great Basin, Steamboat Springs may be the only one that is forming an epithermal ore deposit now. Long Valley, Calif., may also have good possibilities, as may some others if Au is almost totally deposited below the surface. Coso, Calif., is difficult to evaluate from its sinter compositions; total sinter is meager, and the system has discharged at the surface only briefly in the past when the water table was higher than at present. Most of the thermal discharge from this system must be subsurface into ground water under the basin to the east or, possibly, in other directions.

Present data suggest that the disseminated deposits differ in several important respects from epithermal veins, but further detailed systematic study is necessary.

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