Assessment of Geothermal Resources of the United States—1975

# Hydrothermal Convection Systems

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In hydrothermal convection systems, most of the heat is transferred by the convective circulation of water or steam rather than by thermal conduction through solid rocks. Convection occurs in rocks of adequate permeability because of the buoyancy effect of heating and consequent thermal expansion of fluids in a gravity field. The heated fluid tends to rise, and the more dense, cooler fluid tends to descend elsewhere in the system. Convection, by its nature, tends to increase temperatures at higher levels as temperatures at lower levels decrease below those that would otherwise exist.

Worldwide experience gained from geothermal exploration of hydrothermal convection systems indicates that most systems contain liquid water as the dominant pressure-controlling fluid in fractures and pores. Wells drilled into such systems normally deliver at the wellhead a mixture of liquid water and 10 to 30 percent of steam, which forms in the well bore as pressures decrease upward. In a few systems, however, such as Larderello, Italy, and The Geysers, California, wells produce saturated or even superheated steam, typically with no associated liquid. Moreover, inhole pressures measured in shut-in wells of these systems normally increase only slightly with depth within the reservoir; the increase in pressure is equivalent to that of a column of steam and associated gases and is much less than the pressure gradient in a column of water. Pressures in these relatively rare systems evidently are controlled by vapor rather than by liquid, and thus the systems are called vapor-dominated systems.

## VAPOR-DOMINATED SYSTEMS

There is still divided opinion on the origin and fundamental characteristics of vapor-dominated geothermal systems and on why they differ so much in their production characteristics from the more abundant hot-water systems (Truesdell and White, 1973). All successful wells in the Geysers field, the outstanding example of this type of system in the United States, produce saturated or slightly superheated steam containing little or no liquid water and only a small percentage of other gases. Some successful wells initially discharge some water that dries up to pure vapor with time. In-hole temperatures prior to much production tend to be close to 240°C if reservoir depths are greater than about 400 m; initial wellhead pressures are close to 34 bars (James, 1968; Ramey, 1970; White and others, 1971). These characteristics are generally accepted as typical of the deeper "virgin" parts of The Geysers, Larderello, Italy, and Matsukawa, Japan.[1]

The stored heat of the reservoir rocks is probably 85 percent or more of the total heat in the vapor-dominated systems (Truesdell and White, 1973). Production of steam from a reservoir results in a decline in pressures; consequently, water in the pores boils to steam, utilizing heat stored in the reservoir rocks.

Many aspects of vapor-dominated systems are

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[1] Other types of vapor-dominated systems exist, such as those near Monte Amiata, Italy (lower in temperature and much higher in gases other than steam; White, 1973, p. 87, 88; Truesdell and White, 1973), and those found in shallow regimes between ground surface and the water table under local topographic highs of hot-water systems. But in this report, the term "vapor dominated" refers to high-temperature low-gas systems such as The Geysers and Larderello.

not well understood, and critical observations within and below the reservoirs either have not been made, or the data have not yet been released by the operating companies. Our interpretations, however, favor steam as the continuous pressure-controlling fluid in the reservoir, but with liquid water being locally available in small pore spaces and on fracture surfaces. Because of surface tension, this water cannot be drained completely by gravity. Below the vapor-dominated reservoir, we envision a deep water table with underlying rocks saturated with water, probably a high-chloride brine (Truesdell and White, 1973). Estimates of reserves and resources of vapor-dominated systems (Nathenson and Muffler, this circular) are based on this model.

Vapor-dominated systems are considered to develop initially from hot-water systems that have a very large supply of heat but a very low rate of recharge of new water. If the heat supply of a developing system becomes great enough to boil off more water than can be replaced by recharge, a vapor-dominated system starts to form. The fraction of discharged fluid that exceeds recharge is supplied from water previously stored in large fractures and pore spaces. Heat, supplied by condensation of rising steam, is conducted outward from the near-surface, nearly impermeable margins of the reservoir and thus accounts for the high conductive heat flows of these systems. The liquid condensate is in excess of the liquid that can be retained by surface tension; the excess drains downward under gravity to the hypothesized deep water table where it is available for recycling along with newly recharged water.

Our model requires that fluid in excess of that provided by recharging water must be discharged from the system. This feature has important consequences, if true, in that it requires identifiable vent areas. A small vapor-dominated system perhaps could discharge some steam and other gases into surrounding liquid-saturated ground with no conspicuous surface evidence for its existence, but we are skeptical that a large system with high total heat flow and high rate of discharge of steam and other gases can remain concealed without developing the prominent vent areas that characterize all known vapor-dominated systems of this type. The low-temperature, high-gas systems similar to Monte Amiata, Italy (White, 1973, p. 86–87), probably have impermeable cap rocks and little or no surface evidence. Such systems can be considered as thermal natural-gas fields that are high in $CO_2$ and $H_2S$, relatively low in temperature, and at least in part characterized by water drive.

*Identified systems*

The Geysers, California, is the only example of a large vapor-dominated system extensively drilled in the United States (table 3). The extent of the field is not yet known, but the drilling pattern established by more than 100 wells suggests that the commercial limits may have been attained a little northwest of the Sulphur Bank section (about 2 km northwest of the first producing wells at The Geysers). Step-out wells have shown the field to extend at least 3½ km north and 2½ km southwest of the first wells. Drilling is not yet complete to the southeast, but a belt 2 to 5 km wide, 15 km long, and about 70 km$^2$ in total area is our present estimate of the extent of the field. Most commercial wells are 1¼ to 2½ km deep, ranging from about 0.2 km in some of the early wells to a present maximum near 3 km. The heat reservoir is assumed to be continuous between 1 and 3 km in depth; thus, its assumed volume is 140 km$^3$. If the average temperature is 240°C, as we assume, then the estimated total heat content is $18.9 \times 10^{18}$ cal.

The Mud Volcano system in Yellowstone Park was first recognized by its surface characteristics and geochemistry as a probable vapor-dominated system and later confirmed by a single research drill hole (White and others, 1971). The area of surface activity is about 5 km$^2$. Resistivity data (Zohdy and others, 1973) suggest that the vapor-dominated part extends to a depth of 1 to 1½ km and is underlain by a better electrical conductor, presumably a deep water table. The vapor-dominated part is assumed to extend from 0.2 to 1.5 km in depth, and its calculated volume is 6.5 km$^3$. If its average temperature is 230°C, then its estimated heat content is $\sim 0.8 \times 10^{18}$ cal.

*Outlook for new discoveries*

All recognized vapor-dominated systems of the Larderello type are characterized by prominent vent areas with bleached rocks, scanty vegetation, acid-sulfate springs, and no closely associated chloride waters. If these systems do require such vent areas, then few similar unrecognized systems exist for future discovery. The principal possibilities known to us are in Yellowstone National Park and Mount Lassen Volcanic National Park.

Yellowstone Park includes several possible systems other than the Mud Volcano system. The rather young sinter of the Mud Volcano system (White and others, 1971) indicates evolution from a hot-water system soon after the last glacial stage (about 10,000 years ago). This evidence, combined with the resistivity data that suggest a relatively small system saturated with water at depths below about 1½ km, implies a still-evolving system. During the last glacial stage, thick glacial ice and consequent deep meltwater lakes over the thermal areas may have provided high water pressures that resulted in much recharge down the present discharge channels, thereby insuring a water-saturated system. Thus, a vapor-dominated system may become a hot-water system during glaciation. If this is so, then other systems in Yellowstone Park may also have shallow vapor-dominated reservoirs that are still developing.

The thermal activity within the boundaries of Mount Lassen Volcanic National Park has the characteristics of vapor-dominated systems, with chloride waters being completely absent. However, the Morgan Spring group, just outside of the park and about 8 km south of the thermal activity in the park, is a high-temperature chloride-water system that discharges at an altitude of ½ to 1 km below the surface springs in the park. Morgan Springs may be draining the deep chloride part of a large vapor-dominated system within the park.

## HOT-WATER SYSTEMS

*General characteristics*

Hot-water systems (White, 1973) are dominated by circulating liquid, which transfers most of the heat and largely controls subsurface pressures (in contrast to vapor-dominated systems). However, some vapor may be present, generally as bubbles dispersed in the water of the shallow low-pressure parts of these systems.

Most known hot-water systems are characterized by hot springs that discharge at the surface. These springs, through their chemical composition, areal distribution, and associated hydrothermal alteration, have provided very useful evidence on probable subsurface temperatures, volumes, and heat contents. However, springs cannot discharge from convection systems that are capped by impermeable rocks or that exist where the local water table is below the ground surface. Both of these exceptions exist, and many other examples are likely to be discovered.

The temperatures of hot-water systems range from slightly above ambient to about 360°C in the Salton Sea system and the nearby Cerro Prieto system of Mexico. For convenience in this assessment, hot-water convection systems are divided into three temperature ranges: (1) above 150°C (table 4 and figs. 1 and 2); these systems may be considered for generation of electricity; (2) from 90°C to 150°C (table 5 and figs. 2 and 3); these systems are attractive for space and process heating; and (3) below 90°C(not tabulated); these systems are likely to be utilized for heat only in locally favorable circumstances in the United States.

Direct temperature measurements are made either in surface springs or in wells. The temperatures of springs generally do not exceed the boiling temperature at existing air pressure (100°C at sea level to 93°C for pure water at an altitude of ~2,200 m), although some springs in Yellowstone Park and elsewhere are superheated by 1° to 2°C. At depth in wells, where pressures are much higher, the boiling temperature is also much higher. Wells that tap water initially at temperatures above surface boiling yield a mixture of water and steam ("flash" steam), with proportions depending mainly on the initial water temperature and the pressure in the steam-water separator. For example, water flashed from 300°C to a separator pressure of 4.46 bars (50 lb/in$^2$), near a common operating pressure, yields 33 percent steam; 200°C yields 11 percent, but 150°C (just at boiling for the pressure) yields none (Muffler, 1973, p. 255, fig. 28). Obviously the favorability of a hot-water system for generation of electricity from flashed steam increases rapidly above 150°C. Binary systems may allow utilization of somewhat lower temperatures for generation of electricity.

The waters of these systems range from very low salinity to brines of extreme salinity. The most common range is from 0.1 to 1 percent

(Text resumes on p. 51)

**Table 3.—Identified vapor-dominated systems of the United States**

| Location | | | Temperatures °C | | | |
|---|---|---|---|---|---|---|
| Name | Latitude ° ' N | Longitude ° ' W | Surface 1/ | Geochemical SiO$_2$ 2/ | Geochemical Na-K-Ca 2/ | Subsurface 3/ |
| The Geysers, CA | 38 48 | 122 48 | 101 | (not applicable) | | ∿240 |
| Mt. Lassen Nat'l Park, CA | 40 26 | 121 26 | 95½ | (not applicable) | | ∿240 |
| Mud Volcano system Yellowstone Nat'l Park, Wyoming | 44 37.5 | 110 26 | ∿90 | (not applicable) | | ∿230 |
| Totals for 3 systems | | | | | | |

Note: Yellowstone and Mt. Lassen National Parks permanently withdrawn from exploitation.

1/Maximum surface temperature reported from a spring or well.

2/Predicted using geothermometers, assuming last equilibration in the reservoir.

3/Average reservoir temperature based on geothermometry unless otherwise noted in comments.

with probable subsurface temperatures exceeding 200 °C

| Reservoir Assumptions | | | | Comments |
|---|---|---|---|---|
| Sub-surface area km$^2$ 4/ | Thickness km 5/ | Volume km$^3$ 6/ | Heat content $10^{18}$ cal 7/ | |
| 70 | 2.0 | 140 | 18.9 | Area may range from 50 to 100 km$^2$ ; bottom of reservoir may extend below assumed -3 km. >100 well's drilled by early 1975. Present heat production ∿80 times estimated natural heat flow. |
| ∿47 | 1.0 | 47 | 6.3 | Likely to be a vapor-dominated system but not confirmed. |
| 5 | 1.3 | 6.5 | 0.8 | Reservoir assumed ∿0.2 to 1.5 km thickness underlain by hot-water system indicated by resistivity survey. |
| ∿122 | | ∿194 | ∿26 | |

4/From surface manifestations, geophysical data, well records and geologic inference. Assume ∿1.5 km$^2$ if no data pertinent to size is available.

5/Top assumed at 1.5 km of no data on depth available. Bottom assumed to be-3 km for all systems.

6/Calculated from area and thickness.

7/Calculated as product of assumed volume, volumetric specific heat of 0.6 cal/cm$^3$°C, and temperature in degrees above mean annual surface temperature (assumed to be 15°C).

Table 4.—Identified hot-water convection systems

| Name | Location | | Temperatures °C | | | |
|---|---|---|---|---|---|---|
| | Latitude ° ' N | Longitude ° ' W | Surface 1/ | Geochemical 2/ $SiO_2$ | 2/ Na-K-Ca | Subsurface 3/ |
| ALASKA | | | | | | |
| Geyser Bight | 53 13 | 168 28 | 100 | 210 | 236 | 210 |
| Hot Springs Cove | 53 14 | 168 21 | 89 | 131 | 154 | 155 |
| Shakes Springs | 56 43 | 132 02 | 52 | 142 | 175 | 155 |
| Hot Springs Bay | 54 10 | 165 50 | 83 | 152 | 179 | 180 |
| ARIZONA | | | | | | |
| Power Ranch Wells | 33 17.1 | 111 41.2 | | | | 180 |

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1/ Maximum surface temperature reported from a spring or fumarole.
2/ Predicted using chemical geothermometers, assuming last equilibration in the reservoir; assumes saturation of $SiO_2$ with respect to quartz, and no loss of Ca from calcite deposition.
3/ Assumed average reservoir temperature based on data presently available.
4/ From surface manifestations, geophysical data, well records and geologic inference. Assumes 1.5 km$^2$ if no data pertinent to size is available.
5/ Top assumed at depth of 1.5 km if no data available. Bottom assumed at 3 km depth for all convection systems.
6/ Calculated from assumed area and thickness.
7/ Calculated as product of assumed volume, volumetric specific heat of 0.6 cal/cm$^3$ °C, and temperature in degrees C above 15°C.

with indicated subsurface temperatures above 150°C

| Reservoir Assumptions | | | | |
|---|---|---|---|---|
| Subsurface area km² 4/ | Thickness km 5/ | Volume km³ 6/ | Heat content $10^{18}$ cal 7/ | Comments |
| 4 | 2 | 8 | .9 | 22 springs and geysers in 3 thermal areas in 2 km long zone, near Okmok Caldera; siliceous sinter deposit. |
| 2 | 2 | 4 | .3 | Hot springs and geysers in area about 1 km² near Okmok caldera. |
| 1.5 | 1.5 | 2.25 | .2 | Several springs discharging ∿380 lpm; chemical data not reliable. |
| 1.5 | 1.5 | 2.25 | .2 | Hot springs and fumaroles on active Akutan volcano. |
| 2.5(?) | 1 | 2.5 | .2 | No natural springs; two wells ∿1 km apart drilled to 3 km depth with bottom-hole temperatures of 163°C and 184°C; discharge estimated 19,000 l/min. from below 2 km. |

**Table 4.—Identified hot-water convection systems with**

| Name | Location: Latitude ° ' N | Location: Longitude ° ' W | Temperatures °C: Surface 1/ | Temperatures °C: Geochemical $SiO_2$ 2/ | Temperatures °C: Geochemical Na-K-Ca 2/ | Temperatures °C: Subsurface 3/ |
|---|---|---|---|---|---|---|
| CALIFORNIA | | | | | | |
| Surprise Valley | 41 40 | 120 12 | 97 | 174 | 159 | 175 |
| Morgan Springs | 40 23 | 121 31 | 95 | 190 | 229 | 210 |
| Sulphur Bank mine | 39 01 | 122 39 | 80 | 181 | 157 | 185 |
| Calistoga | 38 34.9 | 122 34.4 | | 157 | 155 | 160 |
| Skagg's H.S. | 38 41.6 | 123 01.5 | 57 | 150 | 153 | 155 |
| Long Valley | 37 40 | 118 52 | 94 | 219 | 238 | 220 |
| Red's Meadow | 37 37 | 119 04.5 | 49 | 161 | 130 | 165 |
| Coso H.S. | 36 03 | 117 47 | 95 | 161 | 238 | 220 |
| Sespe H.S. | 34 35.7 | 118 59.9 | 90 | 133 | 155 | 155 |
| Salton Sea | 33 12 | 115 36 | 101 | | | 340 |
| Brawley | 33 01 | 115 31 | | | | 200 |
| Heber | 32 43 | 115 31.7 | | | | 190 |
| East Mesa | 32 47 | 115 15 | | | | 180 |
| Border | 32 44 | 115 07.6 | | | | 160 |

indicated subsurface temperatures above 150°C—Continued

| Reservoir Assumptions | | | | |
|---|---|---|---|---|
| Sub-surface area km² 4/ | Thickness km 5/ | Volume km³ 6/ | Heat content $10^{18}$ cal 7/ | Comments |
| 125 | 2 | 250 | 24 | 7 spring groups, in area of hydrothermal explosion, 1951; minor sinter, 4 wells drilled; maximum reported 160°C, mixing models as high as 225°C. |
| 5 | 2 | 10 | 1.2 | 25 springs flowing 350 lpm; and considerable sinter; system may be much larger, if connected to Lassen. |
| 2.5 | 1.5 | 3.75 | .4 | Springs discharging into water-filled open pit of large mercury deposit; 4 wells drilled, reported maximum 182°C. |
| 4.5 | 2 | 9 | .8 | 4 hot springs and several flowing wells; spring discharge about 30 lpm. |
| 2 | 1.5 | 3 | .3 | 3 springs, flowing 57 lpm. |
| 225 | 2 | 450 | 55 | Springs and fumaroles in area of about 10 km². Recent caldera; about 10 wells drilled, reported to 181°C, extensive geology and geophysics. |
| 1.5 | 1.5 | 2.25 | .2 | 5 springs flowing 38 lpm. |
| 168 | 2 | 336 | 41 | 1 group of hot springs; weak fumarole areas; geophysics indicates may be a very large system. |
| 1.5 | 1.5 | 2.25 | .2 | 4 hot springs flowing 470 lpm. |
| 54 | 2 | 108 | 21 | Many low-temperature seeps; 1 group to 101°C, now under Salton Sea; numerous drill holes to 2400 m and temperatures to 360°C in hypersaline brine. |
| 18 | 1.5 | 27 | 3 | No surface discharge, reported high temperature based on old oil test; size based on temperature-gradient survey. |
| 50 | 2 | 100 | 11 | No surface discharge; much active exploration but no data released; estimated using temperature gradient data and exploration activity. |
| 28 | 2 | 56 | 5.5 | No surface discharge; temperature estimated using drilling data, volume from temperature gradient data and drill-hole data. |
| 3 | .6 | 1.8 | 0.2 | No surface discharge; estimated from temperature gradient data and extrapolation of East Mesa geology. |

**Table 4.—Identified hot-water convection systems with**

| Location | | | Temperatures °C | | | |
|---|---|---|---|---|---|---|
| Name | Latitude ° ' N | Longitude ° ' W | Surface | Geochemical | | Subsurface |
| | | | 1/ | 2/ $SiO_2$ | 2/ Na-K-Ca | 3/ |
| IDAHO | | | | | | |
| Big Creek H.S. | 45 18.8 | 114 19.2 | 93 | 160 | 175 | 175 |
| Sharkey H.S. | 45 00.9 | 113 51.1 | 52 | 135 | 175 | 175 |
| Weiser area | 44 17.9 | 117 02.9 | 77 | 157 | 142 | 160 |
| Crane Creek | 44 18.3 | 116 44.7 | 92 | 173 | 166 | 180 |
| Near Cambridge | 44 34.4 | 116 40.7 | 26 | 119 | 180 | 180 |
| Wardrop H.S. | 43 23.0 | 114 55.9 | 66 | 120 | 155 | 155 |
| Murphy H.S. | 42 02.2 | 115 32.4 | 51 | 127 | 160 | 160 |
| NEVADA | | | | | | |
| Baltazor H.S. | 41 55.3 | 118 42.7 | 80 | 165 | 152 | 170 |
| Pinto H.S. | 41 21 | 118 47 | 93 | 162 | 176 | 165 |
| Great Boiling (Gerlach) Springs | 40 39.7 | 119 21.7 | 86 | 167 | 205 | 170 |
| Hot Sulphur Springs | 41 28.2 | 116 09.0 | 90 | 167 | 184 | 185 |
| Near Wells | 41 10.9 | 114 59.4 | 61 | 140 | 181 | 180 |
| Sulphur H.S. | 40 35.2 | 115 17.1 | 93 | 183 | 181 | 190 |

indicated subsurface temperatures above 150°C—Continued

| Reservoir Assumptions | | | | |
|---|---|---|---|---|
| Sub-surface area km$^2$ 4/ | Thickness km 5/ | Volume km$^3$ 6/ | Heat content $10^{18}$ cal 7/ | Comments |
| 2 | 1.5 | 3 | .3 | 15 springs discharging ∿280 lpm and depositing travertine and sinter; mixing model suggests 220°C; few wells. |
| 2 | 1.5 | 3 | .3 | Spring discharging ∿30 lpm; travertine and sinter(?) reported; Na-K-Ca may be inaccurate; mixing temperature 220°C. |
| 35 | 2 | 70 | 6.1 | Numerous hot springs and wells; at depth may be connected to Crane Creek. Mixing model indicates possible 228°C. |
| 30 | 2 | 60 | 5.9 | Springs discharging ∿200 lpm; extensive sinter, in area of mercury mineralization; Crane Creek and Weiser may be separate in a zone from Midvale, ID to Vale, OR. Mixing model indicates possible 239°C. |
| 1.5 | 1.5 | 2.25 | .2 | Flowing well; Na-K-Ca may be inaccurate. |
| 1.5 | 1.5 | 2.25 | .2 | Numerous springs discharging ∿730 lpm; may be part of a larger system in Camas Prairie; mixing model suggests 160°C. |
| 1.5 | 1.5 | 2.25 | .2 | 2 springs discharging ∿260 lpm; mixing model suggests 200°C. |
| 1.5 | 2 | 3 | .3 | Springs discharging 100 lpm; flowing well 90°C, discharging 25 lpm; the area may be large southern extension of Alvord Desert, OR. area. |
| 5 | 1.5 | 7.5 | .7 | Two areas, probably interconnected; 2 springs of eastern area depositing travertine and and discharging 500 lpm; 1 well,western area, flowing 100 lpm. Na-K-Ca may be inaccurate. |
| 10 | 2.5 | 25 | 2.3 | 2 major groups of springs and 4 others; surface discharge ∿1,000 lpm, calculated total discharge (from heat flow) ∿2040 lpm; well ∿150 m deep, 110°C. |
| 1.5 | 1.5 | 2.25 | .2 | Springs with abundant sulfur. |
| 1.5 | 1.5 | 2.25 | .2 | 3 springs discharging 45 lpm; may be part of a more extensive system extending for 4.8 km along the west edge of the Snake Mountains. |
| 4 | 2.5 | 10 | 1.1 | Many springs and pools in an area of about .5 km$^2$; abundant sinter. |

Table 4.—Identified hot-water convection systems with

| | Location | | Temperatures °C | | | |
|---|---|---|---|---|---|---|
| Name | Latitude ° ' N | Longitude ° ' W | Surface 1/ | Geochemical 2/ $SiO_2$ | 2/ Na-K-Ca | Subsurface 3/ |
| NEVADA Con. | | | | | | |
| Beowawe H.S. | 40 34.2 | 116 34.8 | | 226 | 242 | 240 |
| Kyle H.S. | 40 24.5 | 117 52.9 | 77 | 161 | 211 | 180 |
| Leach H.S. | 40 36.2 | 117 38.7 | 96 | 155 | 176 | 170 |
| Hot Springs Ranch | 40 45.7 | 117 29.5 | 85 | 150 | 180 | 180 |
| Jersey Valley H.S. | 40 10.7 | 117 29.4 | 29 | 143 | 182 | 185 |
| Stillwater area | 39 31.3 | 118 33.1 | 96 | 159 | 140 | 160 |
| Soda Lake | 39 34 | 118 49 | 90 | 165 | 161 | 165 |
| Brady H.S. | 39 47.2 | 119 00 | 98 | 179 | | 214 |
| Steamboat Springs | 39 23. | 119 45 | 96 | 207 | 226 | 210 |
| Wabuska H.S. | 39 09.7 | 119 11 | 97 | 145 | 152 | 155 |
| Lee H.S. | 39 12.6 | 118 43.4 | 88 | 173 | 162 | 175 |
| Smith Creek Valley | 39 21.4 | 117 32.8 | 86 | 143 | 157 | 160 |

**indicated subsurface temperatures above 150 °C—Continued**

| Reservoir Assumptions | | | | |
|---|---|---|---|---|
| Subsurface area km$^2$ 4/ | Thickness km 5/ | Volume km$^3$ 6/ | Heat content $10^{18}$ cal 7/ | Comments |
| 21 | 2 | 42 | 5.7 | Prior to exploration, about 50 springs and small geysers discharging about 400 lpm from extensive area of sinter deposits; 6 wells drilled up to 600m depth, temperatures to 212°C, 1 deep well but no data available. |
| 1.5 | 1.5 | 2.25 | .2 | Several springs, largest flowing ∿20 lpm depositing travertine. Na-K-Ca thermometry may be to high. |
| 4 | 2.5 | 10 | .9 | Several hot springs discharging ∿760 lpm; calculated total flow ∿900 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | Several springs, largest discharging ∿100 lpm and depositing travertine so Na-K-Ca may be inaccurate. |
| 1.5 | 1.5 | 2.25 | .2 | One (3) spring discharging only 20 lpm in area of sinter and travertine; surface temperature low because of low discharge. |
| 10 | 2.5 | 25 | 2.2 | No surface springs, but hot wells at least to 115°C; calculated total discharge (from heat flow) ∿6,000 lpm. |
| 5 | 2.5 | 12.5 | 1.1 | No surface discharge, but small area altered by gases, and 21 km$^2$ of anomalous heat flow. Shallow wells show 100°C near surface; between 2 recent basaltic eruptive centers. |
| 12 | 2.5 | 30 | 3.6 | Several former springs discharged ∿200 lpm from small area of sinter; several wells; 214°C reported in 1500 m well; calculated discharge ∿2,700 lpm. |
| 6 | 2.7 | 16 | 1.9 | About 70 springs discharging ∿250 lpm from extensive sinter deposits with ages at least as much as 1 million years, calculated total discharge ∿4,300 lpm; more than 20 wells for research, exploration, and spa supply. |
| 1.5 | 1.5 | 2.25 | .2 | Several hot springs of low natural discharge discharge; three wells drilled to maximum of ∿670 m, up to 106°C; small area of travertine; area may be larger. |
| 1.5 | 1.5 | 2.25 | .2 | Several springs discharging ∿130 lpm from area of sinter. |
| 1.5 | 1.5 | 2.25 | .2 | Several springs, minor travertine. |

**Table 4.—Identified hot-water convection systems with**

| Name | Location<br>Latitude ° ' N | <br>Longitude ° ' W | Temperatures °C<br>Surface 1/ | <br>Geochemical SiO2 2/ | <br>Geochemical Na-K-Ca 2/ | <br>Subsurface 3/ |
|---|---|---|---|---|---|---|
| NEW MEXICO | | | | | | |
| Valles Caldera | 35 43 | 106 32 | 87 | | | 240 |
| Lightning Dock area | 32 08.5 | 108 50 | 99 | 156 | 169 | 170 |
| OREGON | | | | | | |
| Mickey H.S. | 42 40.5 | 118 20.7 | 73 | 180 | 207 | 210 |
| Alvord H.S. | 42 32.6 | 118 31.6 | 76 | 148 | 199 | 200 |
| Hot Lake | 42 20.1 | 118 36.0 | 96 | 165 | 176 | 180 |
| Vale H.S. | 43 59.4 | 117 14.1 | 73 | 153 | 158 | 160 |
| Neal H.S. | 44 01.4 | 117 27.6 | 87 | 173 | 181 | 180 |
| Lakeview | 42 12.0 | 120 21.6 | 96 | 157 | 143 | 160 |
| Crumps Spring | 42 15.0 | 119 53.0 | 78 | 173 | 144 | 180 |
| Weberg H.S. | 44 00 | 119 38.8 | 46 | 125 | 170 | 170 |

indicated subsurface temperatures above 150°C—Continued

| Reservoir Assumptions | | | | |
|---|---|---|---|---|
| Subsurface area km$^2$ 4/ | Thickness km 5/ | Volume km$^3$ 6/ | Heat content $10^{18}$ cal 7/ | Comments |
| 65 | 2 | 130 | 18 | Pleistocene caldera with 1 group acid-sulfate springs (Sulphur Springs) and very extensive hydrothermal alteration; more than 6 geothermal wells drilled, but no detailed data available; suspected as having small vapor-dominated cap underlain by high-chloride hot-water system with temperatures over 240°C. |
| 1.5 | 1.5 | 2.25 | .2 | No surface springs; shallow water wells at boiling. The area may be much more extensive. Drill hole 3 km to north showed 121°C at 2 km depth. Better estimate may be avg T = 130°C, area 4 km$^2$, thickness 2 km, heat content .5 x $10^{18}$ cal. |
| 6 | 2 | 12 | 1.4 | Several springs discharging ∿100 lpm and depositing sinter; surface manifestations over 0.1 km$^2$. |
| 3 | 1.5 | 4.5 | .5 | Several springs in area of .5 km$^2$ discharging ∿500 lpm. If Hot Lake, Mickey, and Alvord H.S. are one large system with temperature as at Mickey, the heat content would be 30 x $10^{18}$ cal; three separate systems is preferred model. |
| 6 | 2 | 12 | 1.2 | Thermal springs and 1 very large pool (lake) discharging surface manifestations over 0.1 km$^2$. Small spring N. of Hot Lake, 98°C. |
| 50 | 2 | 100 | 8.7 | Hot springs discharging ∿75 lpm; large area indicated. |
| 2 | 2 | 4 | .4 | 1 spring discharging ∿90 lpm. |
| 8 | 2 | 16 | 1.4 | About 16 springs including Hunter's and Barry Ranch discharging ∿2,500 lpm in an area of ∿5 km$^2$; several wells at Hunter's for heating spa. |
| 4 | 2 | 8 | .8 | Spring and well (121°C at 505 m) that has erupted as a geyser; discharging 0 to 50 lpm; in small area of sinter. |
| 1.5 | 1.5 | 2.25 | .2 | Hot spring discharging 40 lpm. |

Table 4.—Identified hot-water convection systems wit

|  | Location |  | Temperatures °C |  |  |  |
|---|---|---|---|---|---|---|
| Name | Latitude ° ' N | Longitude ° ' W | Surface 1/ | Geochemical 2/ $SiO_2$ | Geochemical 2/ Na-K-Ca | Subsurface 3/ |
| UTAH |  |  |  |  |  |  |
| Roosevelt (McKean) H.S. | 38 30 | 112 50 | 88 | 213 | 283 | 230 |
| Cove Fort-Sulphurdale | 38 36 | 112 33 | -- |  |  | 200 |
| Thermo H.S. | 38 11 | 113 12.2 | 90 | 144 | 200 | 200 |
| WASHINGTON |  |  |  |  |  |  |
| Baker H.S. | 48 45.9 | 121 40.2 | 42 | 151 | 162 | 165 |
| Gamma H.S. | 48 10 | 121 02 | 60 | 161 | 220 | 165 |
| Kennedy H.S. | 48 07 | 121 11.7 | 43 | 155 | 199 | 160 |
| Longmire H.S. | 46 45.1 | 121 48.7 | 21 | 169 | 168 | 170 |
| Summit Creek (Soda) | 46 42.2 | 121 29.0 | 13 | 169 | 161 | 170 |
| WYOMING |  |  |  |  |  |  |
| Yellowstone National Park | 44 36 | 110 30 | ~96 | 250 | 270 | 250 |
| Totals (63 systems) |  |  |  |  |  |  |

indicated subsurface temperatures above 150°C—Continued

| Reservoir Assumptions | | | | |
|---|---|---|---|---|
| Sub-surface area km$^2$ 4/ | Thickness km 5/ | Volume km$^3$ 6/ | Heat content $10^{18}$ cal. 7/ | Comments |
| 4 | 2 | 8 | 1.0 | Hot springs decreasing from 88°C (1908) to 55°C (1957), then ceased discharging from $SiO_2$ sealing; extensive siliceous sinter; area and volume may be much larger. |
| 15 | 1.5 | 22.5 | 2.5 | No springs but active gas seeps; altered areas mined for sulfur; no reliable chemical data; possibly a vapor-dominated system. |
| 1.5 | 1.5 | 2.25 | .2 | 16 springs in 2 groups; travertine deposits. |
| 1.5 | 1.5 | 2.25 | .2 | 1 (?) spring discharging 26 lpm and possibly depositing calcite. |
| 1.5 | 1.5 | 2.25 | .2 | |
| 1.5 | 1.5 | 2.25 | .2 | 4 springs discharging ∿110 lpm, in extensive travertine deposits. |
| 1.5 | 1.5 | 2.25 | .2 | Spring deposits, not identified; in Mt. Ranier National Park; chemical temperatures not reliable. |
| 1.5 | 1.5 | 2.25 | .2 | Chemical temperatures not reliable. |
| 375 | 2.5 | 940 | 133 | Numerous thermal phenomena, largely in Yellowstone caldera; individual areas not itemized; total discharge ∿185,000 lpm; 13 research drill holes with maximum T 237.5°C at 332 m; other geochemical and mixing-model T's indicate 330°C. |
| ∿1414 | | ∿2995 | ∿371 | |

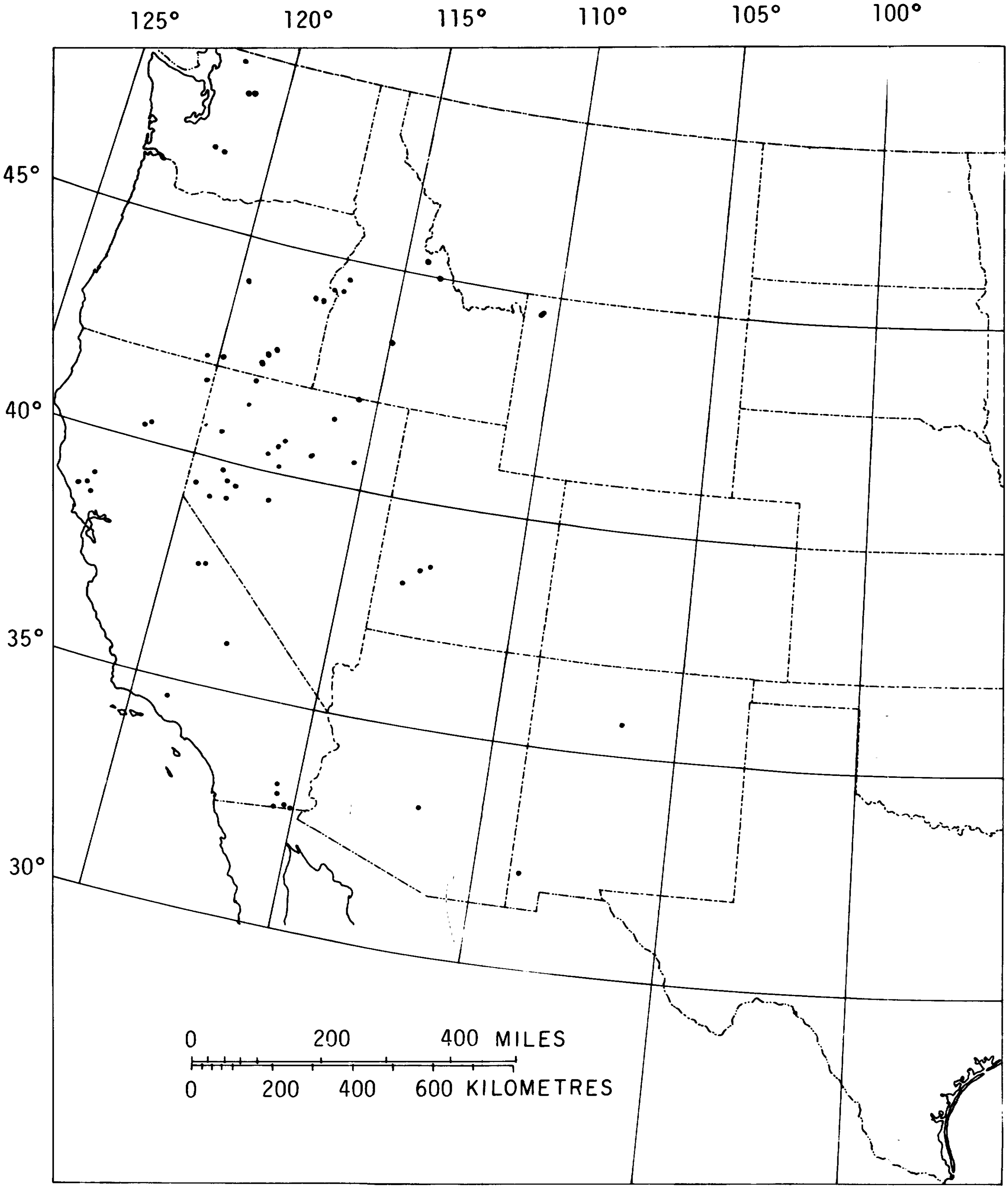

FIGURE 1.—Location of hydrothermal convection systems in the conterminous United States with indicated subsurface temperatures above 150°C.

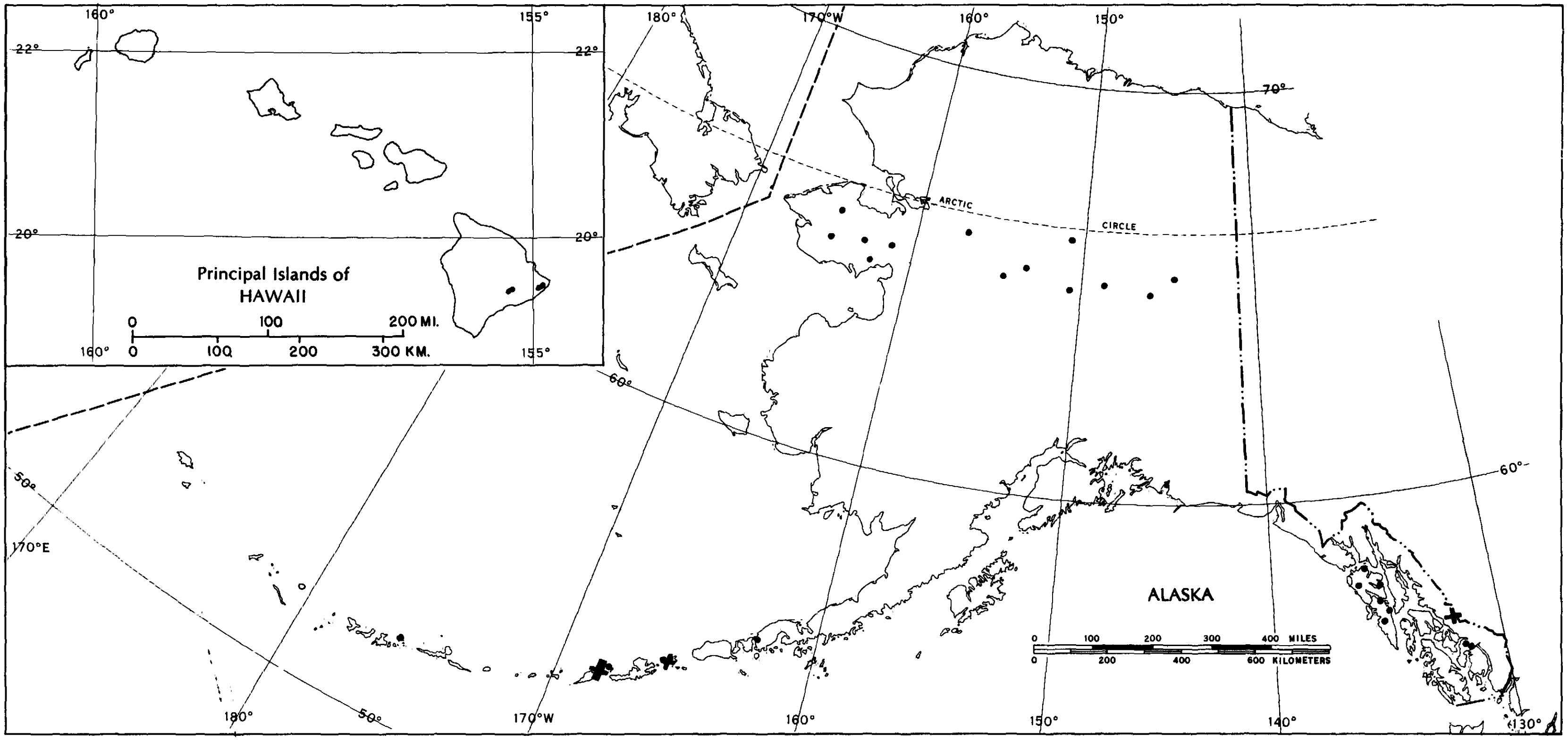

FIGURE 2.—Location of hydrothermal convection systems in Alaska and Hawaii with indicated subsurface temperatures above 150°C (+) and between 90° and 150°C (dots).

## Table 5.—Identified hot-water convection systems with

| Name | Location: Latitude ° ' N | Location: Longitude ° ' W | Temperatures °C: Surface 1/ | Temperatures °C: Geochemical $SiO_2$ 2/ | Temperatures °C: Geochemical Na-K-Ca 2/ | Temperatures °C: Subsurface 3/ |
|---|---|---|---|---|---|---|
| ALASKA | | | | | | |
| Okmok caldera | 53 29 | 168 06 | 100 | 110 | 75 | 125 |
| Great Sitkin Is. | 52 04 | 176 05 | 99 | | | 125 |
| Pilgrim H.S. | 65 06 | 164 55 | 88 | 137 | 146 | 150 |
| Serpentine Sprs. | 65 51 | 164 42 | 77 | 132 | 161 | 140 |
| Near Lava Creek | 65 13 | 162 54 | 65 | 128 | 91 | 130 |
| Clear Creek | 64 51 | 162 18 | 67 | 119 | 83 | 125 |
| Granite Mtn. (Sweepstakes) | 65 22 | 161 15 | 49 | 122 | 75 | 130 |
| South | 66 09 | 157 07 | 50 | 115 | 72 | 120 |
| Melozi H.S. | 65 08 | 154 40 | 55 | 124 | | 130 |
| Little Melozitna | 65 28 | 153 19 | 38 | 126 | | 130 |
| Kanuti | 66 20 | 150 48 | 66 | | 136 | 140 |
| Manley (Baker) H.S. | 65 00 | 150 38 | 59 | 115 | 137 | 140 |
| Tolovana | 65 16 | 148 50 | 60 | 122 | 162 | 130 |
| Chena | 65 03 | 146 03 | 57 | 129 | 137 | 140 |
| Circle | 65 29 | 144 39 | 54 | 135 | 143 | 145 |
| E. Cold Bay | 55 13 | 162 29 | 54 | 117 | 144 | 145 |
| Near Tenakee Inlet | 58 13 | 135 55 | 82 | 147 | 72 | 150 |
| Hooniah H.S. | 57 48 | 136 20 | 44 | 136 | | 140 |
| Tenakee H.S. | 57 47 | 135 13 | 43 | 111 | 63 | 115 |

1/ Maximum surface temperature reported from a spring or fumarole.

2/ Predicted using chemical geothermometers, assuming last equilibration in the reservoir; assumes saturation of $SiO_2$ with respect to quartz, and no loss of Ca from calcite deposition.

3/ Assumed average reservoir temperature based on data presently available.

4/ From surface manifestations, geophysical data, well records, and geologic inference. Assumes 1.5 $km^2$ if no data pertinent to size is available.

5/ Top assumed at depth of 1.5 km if no data available. Bottom assumed at 3 km depth for all convection systems.

6/ Calculated from assumed area and thickness.

7/ Calculated as product of assumed volume, volumetric specific heat of 0.6 $cal/cm^3{}^\circ C$, and temperature in degrees C above 15°C.

indicated subsurface temperatures from 90° to 150°C

| Reservoir Assumptions | | | | Comments |
|---|---|---|---|---|
| Subsurface area km² 4/ | Thickness km 5/ | Volume km³ 6/ | Heat content $10^{18}$ cal 7/ | |
| 3 | 2 | 6 | .4 | About 18 springs near 1945 eruption in Okmok caldera; may be more extensive and higher in temperatures; sinter reported. |
| 1.5 | 1.5 | 2.25 | .2 | 12 springs and fumaroles near recent volcanism. |
| 1.5 | 1.5 | 2.25 | .2 | Several hot springs in permanently thawed area of .25 km². |
| 1.5 | 1.5 | 2.25 | .2 | 2 spring areas 1.3 km apart discharging ∿100 lpm and depositing travertine; Na-K-Ca may be too high. |
| 1.5 | 1.5 | 2.25 | .2 | One main spring. |
| 1.5 | 1.5 | 2.25 | .2 | 2 springs discharging ∿1,000 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | Several springs. |
| 1.5 | 1.5 | 2.25 | .1 | Several springs. |
| 1.5 | 1.5 | 2.25 | .2 | One main spring discharging ∿500 lpm; chemical data not reliable. |
| 1.5 | 1.5 | 2.25 | .2 | Hot springs discharging ∿230 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | Several hot springs. |
| 1.5 | 1.5 | 2.25 | .2 | Hot spring discharging ∿560 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | Several hot springs, "small" discharge, possibly depositing travertine. |
| 1.5 | 1.5 | 2.25 | .2 | Hot springs discharging ∿840 lpm, depositing sulfur |
| 1.5 | 1.5 | 2.25 | .2 | 11 hot springs discharging ∿500 lpm, depositing travertine. |
| 1.5 | 1.5 | 2.25 | .2 | In recent volcanic rocks. |
| 1.5 | 1.5 | 2.25 | .2 | Discharging ∿40 lpm; chemical data not reliable. |
| 1.5 | 1.5 | 2.25 | .2 | 3 hot springs discharging ∿110 lpm; chemical data not reliable. |
| 1.5 | 1.5 | 2.25 | .1 | About 12 hot springs discharging ∿80 lpm. |

Table 5.—Identified hot-water convection systems with indicated

| Name | Location<br>Latitude ° ' N | <br>Longitude ° ' W | Temperatures °C<br>Surface 1/ | <br>Geochemical<br>2/ $SiO_2$ | <br><br>2/ Na-K-Ca | <br>Subsurface 3/ |
|---|---|---|---|---|---|---|
| ALASKA Con. | | | | | | |
| Near Fish Bay | 57 22 | 135 23 | 47 | 143 | | 150 |
| Baranof H.S. | 57 05 | 134 50 | 50 | 119 | 68 | 125 |
| Goddard H.S. | 56 50 | 135 22 | 67 | 148 | 147 | 150 |
| Bailey H.S. | 55 59 | 131 40 | 88 | 158 | | 150 |
| Bell Island H.S. | 55 56 | 131 34 | 72 | 140 | | 145 |
| ARIZONA | | | | | | |
| Verde H.S. | 34 21.5 | 111 42.5 | 36 | 118 | 146 | 150 |
| Castle H.S. | 33 59.1 | 112 21.6 | 50 | 109 | 71 | 110 |
| North of Clifton | 33 04.7 | 109 18.2 | 59 | 138 | 174 | 140 |
| Clifton H.S. | 33 03.2 | 109 17.8 | 75 | 107 | 161 | 110 |
| Eagle Creek Spring | 33 02.8 | 109 28.6 | 36 | 114 | 104 | 115 |
| Gillard H.S. | 32 58.5 | 109 21.0 | 82 | 135 | 138 | 140 |
| Mt. Graham | 32 51.4 | 109 44.9 | 42 | 106 | 102 | 110 |
| CALIFORNIA | | | | | | |
| Kelley H.S. | 41 27.5 | 120 50 | 96 | 144 | 85 | 130 |
| Hunt H.S. | 41 02.1 | 122 55.1 | 58 | 101 | 75 | 105 |
| Big Bend H.S. | 41 01.3 | 122 55.1 | 82 | 121 | 137 | 140 |
| Salt Springs(1) | 40 40.2 | 122 38.7 | 20 | 107 | 55 | 110 |
| Wendel-Amedee area | 40 18 | 120 11 | 95 | 135 | 129 | 140 |

subsurface temperatures from 90° to 150°C—Continued

| Reservoir Assumptions | | | | Comments |
|---|---|---|---|---|
| Subsurface area km² 4/ | Thickness km 5/ | Volume km³ 6/ | Heat content $10^{18}$ cal 7/ | |
| 1.5 | 1.5 | 2.25 | .2 | Springs discharging ∿95 lpm; chemical data not reliable. |
| 1.5 | 1.5 | 2.25 | .2 | Springs discharging ∿300 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 3 hot springs discharging ∿50 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 9 hot springs discharging ∿315 lpm; chemical data not reliable. |
| 1.5 | 1.5 | 2.25 | .1 | 5 hot springs discharging ∿40 lpm; chemical data not reliable. |
| 1.5 | 1.5 | 2.25 | .2 | Several springs; indicated temperatures may be too high. |
| 1.5 | 1.5 | 2.25 | .1 | Two springs. |
| 1.5 | 1.5 | 2.25 | .2 | Two springs; may be depositing calcite |
| 1.5 | 1.5 | 2.25 | .1 | Several springs; may be depositing calcite. |
| 1.5 | 1.5 | 2.25 | .1 | Two springs; indicated geochemical temperature may be too high. |
| 1.5 | 1.5 | 2.25 | .2 | 5 springs |
| 1.5 | 1.5 | 2.25 | .1 | 1 hot mineral well; geochemical temperatures may be too high. |
| 1.5 | 2 | 3 | .2 | 1 spring flowing ∿1,200 lpm; 1,000 m well drilled in 1969, reported 110°C. |
| 1.5 | 1.5 | 2.25 | .1 | 2 hot springs flowing 8 lpm |
| 1.5 | 1.5 | 2.25 | .2 | 6 hot springs, flowing 38 lpm. |
| 1.5 | 1.5 | 2.25 | .1 | Spring from travertine cone, flowing 20 lpm |
| 7 | 2 | 14 | 1.1 | Many flowing 3,500 lpm; 4 wells, deepest 338 m, T=107°C; possibly separate systems at Wendel and Amedee. |

Table 5.—Identified hot-water convection systems with indicated

| Location |  |  | Temperatures °C |  |  |  |
|---|---|---|---|---|---|---|
| Name | Latitude ° ' N | Longitude ° ' W | Surface 1/ | Geochemical $SiO_2$ 2/ | Geochemical Na-K-Ca 2/ | Subsurface 3/ |
| CALIFORNIA Con. |  |  |  |  |  |  |
| Tuscan (Lick) S. | 40 14.5 | 122 08.4 | 30 | 137 | 112 | 140 |
| Soda Spring | 39 24.8 | 122 58.6 | 17 | 148 | 158 | 150 |
| Salt Spring(2) | 39 25.8 | 122 32.3 | 25 | 157 | 123 | 150 |
| Crabtree H.S. | 39 17.4 | 122 49.3 | 41 | 163 | 133 | 150 |
| Fouts (Redeye) S. | 39 21.0 | 122 40.1 | 26 | 150 | 126 | 150 |
| Fouts (Champagne) S. | 39 20.5 | 122 39.4 | 18 | 117 | 128 | 130 |
| Orr's H.S. | 39 13.8 | 123 21.9 | 40 | 112 | 67 | 115 |
| Vichy Springs | 39 09.9 | 123 09.4 | 32 | 132 | 145 | 135 |
| Cooks Springs | 39 15.2 | 122 31.4 | 17 | 133 | 187 | 140 |
| Saratoga Springs | 39 10.5 | 122 58.7 | 16 | 137 | 46 | 140 |
| Wilbur H.S. area | 39 02.2 | 122 25.2 | 60 | 180 | 240 | 145 |
| Deadshot Spring | 39 05.1 | 122 27.4 | 26 | 135 | 204 | 135 |
| Point Arena H.S. | 38 52.6 | 123 30.6 | 44 | 105 | 62 | 105 |
| Ornbaun Springs | 38 54.7 | 123 18.4 | 16 | 126 | 122 | 125 |
| Seigler Springs | 38 52.5 | 122 41.3 | 52 | 169 | 188 | 150 |
| Baker Soda Spring | 38 53.6 | 122 31.9 | 24 | 124 | 202 | 130 |
| One-Shot Mining Co. | 38 50.0 | 122 21.4 | 22 | 135 | 153 | 150 |
| Aetna Springs | 38 39.5 | 122 28.7 | 33 | 135 | 94 | 135 |
| Walter Springs | 38 39.2 | 122 21.4 | 19 | 135 | 82 | 135 |
| Mark West Springs | 38 32.9 | 122 43.2 | 31 | 140 | 48 | 140 |

subsurface temperatures from 90° to 150°C—Continued

| Reservoir Assumptions | | | | Comments |
|---|---|---|---|---|
| Subsurface area km$^2$ 4/ | Thickness km 5/ | Volume km$^3$ 6/ | Heat content $10^{18}$ cal 7/ | |
| 1.5 | 1.5 | 2.25 | .2 | 20 Springs flowing 190 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | High bicarbonate spring; geothermometry doubtful. |
| 1.5 | 1.5 | 2.25 | .2 | Note: distinct from Salt Springs, above; geothermometry doubtful. |
| 1.5 | 1.5 | 2.25 | .2 | 4 springs, flowing 57 lpm; geothermometry doubtful. |
| 1.5 | 1.5 | 2.25 | .2 | 4 springs, flow 7.5 lpm; geothermometry doubtful. |
| 1.5 | 1.5 | 2.25 | .2 | 4 springs, geothermometry doubtful. |
| 1.5 | 1.5 | 2.25 | .1 | 7 springs flowing 95 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 7 springs flowing 113 lpm; Na-K-Ca may be inaccurate due to travertine deposition. |
| 1.5 | 1.5 | 2.25 | .2 | Geothermometry doubtful. |
| 1.5 | 1.5 | 2.25 | .2 | 5 springs, flow 9 lpm; geothermometry doubtful. |
| 16 | 2 | 32 | 2.5 | 12 springs, flow 80 lpm; well drilled to 1,100 m, 141°C; should be in table 4? |
| 1.5 | 1.5 | 2.25 | .2 | 4 springs flowing 4 lpm; geothermometry doubtful. |
| 1.5 | 1.5 | 2.25 | .1 | 2 springs flowing 19 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 1 spring flowing less than 1 lpm. |
| 2 | 1.5 | 3 | .2 | 13 springs flowing 132 lpm; geothermometry doubtful. |
| 1.5 | 1.5 | 2.25 | .2 | Numerous springs; geothermometry doubtful. |
| 1.5 | 1.5 | 2.25 | .2 | Flow 189 lpm; sinter and travertine reported. |
| 1.5 | 1.5 | 2.25 | .2 | 6 springs flowing 75 lpm; geothermometry doubtful. |
| 1.5 | 1.5 | 2.25 | .2 | Flow 6 lpm; geothermometry doubtful. |
| 1.5 | 1.5 | 2.25 | .2 | ∿9 hot springs in a group flowing 113 lpm. |

Table 5.—Identified hot-water convection systems with indicated

| Location | | | Temperatures °C | | | |
|---|---|---|---|---|---|---|
| Name | Latitude ° ' N | Longitude ° ' W | Surface 1/ | Geochemical SiO$_2$ 2/ | Na-K-Ca 2/ | Subsurface 3/ |
| CALIFORNIA Con. | | | | | | |
| Napa Soda S. Rock (Priest) | 38 31.1 | 122 15.6 | 26 | 143 | 81 | 145 |
| Los Guilicos W.S. | 38 23.7 | 122 33.0 | 31 | 129 | 184 | 135 |
| (Jackson's) Napa Soda Springs | 38 23.4 | 122 16.7 | 16 | 149 | 60 | 150 |
| Brockway (Cornelian) H.S. | 39 13.5 | 120 0.4 | 60 | 119 | 94 | 120 |
| Grovers H.S. | 38 41.9 | 119 51.6 | 63 | 135 | 126 | 140 |
| Fales H.S. | 38 20 | 119 24 | 62 | 147 | 165 | 150 |
| Buckeye H.S. | 38 14.3 | 119 19.6 | 64 | 122 | 138 | 140 |
| Benton H.S. | 37 48 | 118 31.8 | 57 | 113 | 79 | 115 |
| Travertine H.S. | 38 14.8 | 119 12.1 | 70 | 114 | 172 | 120 |
| Near Black Pt. | 38 2.4 | 119 5 | 63 | 122 | 124 | 125 |
| Paoha Island | 37 59.8 | 119 01.2 | 83 | 186 | | 125 |
| Mono H.S. | 37 19.5 | 119 01.0 | 44 | 110 | 80 | 115 |
| Blayney Meadows H.S. | 37 14.1 | 118 53 | 43 | 102 | 57 | 105 |
| Mercey H.S. | 36 42.2 | 120 51.6 | 46 | 122 | 94 | 125 |
| Randsburg area | 35 23.0 | 117 32.2 | 115 | | | 125 |
| Arrowhead H.S. area | 34 08.6 | 117.15.2 | 94 | 132 | 147 | 150 |
| Pilger Estates H.S. | 33 26.0 | 115 41.1 | 82 | 125 | 145 | 145 |
| Warner H.S. | 33 17.0 | 116 38.4 | 64 | 141 | 100 | 145 |
| Glamis (E. Brawley) | 32 58 | 115 11 | | | | 135 |
| Glamis (East) | 33 59 | 115 04 | | | | 135 |
| Dunes | 32 49 | 115 01 | | | | 135 |

subsurface temperatures from 90° to 150°C—Continued

| Reservoir Assumptions | | | | Comments |
|---|---|---|---|---|
| Subsurface area km$^2$ 4/ | Thickness km 5/ | Volume km$^3$ 6/ | Heat content $10^{18}$ cal 7/ | |
| 1.5 | 1.5 | 2.25 | .2 | 2 springs flowing 60-85 lpm; geothermometry doubtful. |
| 1.5 | 1.5 | 2.25 | .2 | 3 springs flowing 75 lpm; Na-K-Ca may be inaccurate due to travertine deposition. |
| 1.5 | 1.5 | 2.25 | .2 | 27 springs; geothermometry doubtful. |
| 1.5 | 1.5 | 2.25 | .1 | 6 springs flowing 570 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 12 springs flowing 378 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 20 springs flowing 95 lpm, possibly depositing travertine. |
| 1.5 | 1.5 | 2.25 | .2 | 1 spring flowing 75 lpm. |
| 1.5 | 1.5 | 2.25 | .1 | 2 springs flowing 1,500 lpm. |
| 1.5 | 1.5 | 2.25 | .1 | 3 main springs flowing 38 lpm; extensive travertine. |
| 1.5 | 1.5 | 2.25 | .1 | |
| 1.5 | 1.5 | 2.25 | .1 | Several springs flowing 370 lpm; non-quartz equilibration of $SiO_2$ likely. |
| 1.5 | 1.5 | 2.25 | .1 | Four springs flowing 95 lpm. |
| 1.5 | 1.5 | 2.25 | .1 | Eight springs flowing 150 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 3 hot springs flowing 23 lpm. |
| 1.5 | 2.5 | 3.75 | .3 | 1 well reported 115°C at 235 m. |
| 2 | 1.5 | 3 | .2 | 2 groups of hot springs flowing 190 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | Near Salton Sea; possibly more extensive. |
| 1.5 | 1.5 | 2.25 | .2 | 6 springs flowing 570 lpm. |
| 2 | 1.5 | 3 | .2 | Estimated using temperature gradient data; a part above 150°C? |
| 4 | 1.5 | 6 | .4 | Temperature gradient data; a part above 150°C? |
| 6 | 1.5 | 9 | .6 | Temperature gradient data: a part above 150°C? |

Table 5.—Identified hot-water convection systems with indicated

| | Location | | Temperatures °C | | | |
|---|---|---|---|---|---|---|
| Name | Latitude ° ' N | Longitude ° ' W | Surface 1/ | Geochemical 2/ $SiO_2$ | 2/ Na-K-Ca | Subsurface 3/ |
| COLORADO | | | | | | |
| Routt H.S. | 40 33.6 | 106 51 | 64 | 131 | 168 | 135 |
| Steamboat Springs | 40 29.1 | 106 50.3 | 66 | 129 | 195 | 135 |
| Idaho Springs | 39 44.2 | 105 30.2 | 50 | 109 | 208 | 115 |
| Glenwood Springs | 39 33 | 107 19.3 | 66 | 137 | 190 | 140 |
| Avalanche Springs | 39 13.9 | 107 13.5 | 57 | 136 | 125 | 140 |
| Cottonwood Springs | 38 48.7 | 106 13.5 | 62 | 107 | 83 | 110 |
| Mt. Princeton S. | 38 43.9 | 106 10.2 | 66 | 112 | 52 | 115 |
| Poncha H.S. | 38 29.9 | 106 04.5 | 76 | 129 | 143 | 145 |
| Mineral H.S. | 38 10.1 | 105 55.0 | 63 | 103 | 91 | 105 |
| Waunita H.S. | 38 31.0 | 106 29.1 | 71 | 129 | 87 | 130 |
| Cebolla H.S. | 38 16.5 | 107 05.9 | 46 | 125 | 233 | 130 |
| Orvis H.S. | 38 08 | 107 44 | 58 | 109 | 231 | 110 |
| Wagon Wheel Gap | 37 45 | 106 49.2 | 66 | 129 | 188 | 135 |
| Pagosa H.S. | 37 15.5 | 107 00.5 | 70 | 165 | 278 | 150? |

subsurface temperatures from 90° to 150°C—Continued

| Reservoir Assumptions | | | | Comments |
|---|---|---|---|---|
| Sub-surface area km² 4/ | Thickness km 5/ | Volume km³ 6/ | Heat content $10^{18}$ cal 7/ | |
| 1.5 | 1.5 | 2.25 | .2 | Three hot springs; Chemical data not reliable. |
| 1.5 | 1.5 | 2.25 | .2 | Many hot springs; chemical data not reliable; some travertine. |
| 1.5 | 1.5 | 2.25 | .1 | 8 springs, total discharge 190 lpm depositing travertine; probably fault-controlled; chemical data not reliable. |
| 1.5 | 1.5 | 2.25 | .2 | 11 springs discharging about 11,400 lpm; chemical data not reliable; some travertine. |
| 1.5 | 1.5 | 2.25 | .2 | 5 springs discharging ∿54 lpm; chemical data not reliable. |
| 4 | 1.5 | 6 | .3 | 5 springs discharging ∿570 lpm; extensive zeolitization. |
| 5 | 1.5 | 7.5 | .5 | 4 main springs, 30 others; extensive zeolitization, present deposition of opal, calcite, and phillipsite reported. |
| 1.5 | 1.5 | 2.25 | .2 | 3 springs depositing travertine and discharging ∿1,900 lpm; associated with flourite deposits; Na-K-Ca temperature may be too high. |
| 1.5 | 1.5 | 2.25 | .1 | 30 springs discharging ∿190 lpm, reported with travertine and sinter (?); wells to 354 m depth and 60°C. |
| 1.5 | 1.5 | 2.25 | .2 | 2 groups, more than 100 springs discharging 3,785 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 20 springs discharging ∿380 lpm; travertine reported; chemical data not reliable. |
| 1.5 | 1.5 | 2.25 | .1 | 1 spring discharging ∿1,140 lpm; chemical data not reliable. |
| 1.5 | 1.5 | 2.25 | .2 | 3 springs depositing travertine and associated with flourite deposits; Na-K-Ca temperature probably too high. |
| 1.5 | 1.5 | 2.25 | .2 | Springs discharging ∿380 lpm and depositing travertine; 1 well for space heating; chemical data not reliable. |

**Table 5.—Identified hot-water convection systems with indicated**

| Location | | | Temperatures °C | | | |
|---|---|---|---|---|---|---|
| Name | Latitude ° ' N | Longitude ° ' W | Surface 1/ | Geochemical 2/ $SiO_2$ | 2/ Na-K-Ca | Subsurface 3/ |
| HAWAII | | | | | | |
| Steaming Flats (Sulphur Bank area) | 19 26.5 | 155 16 | 97 | --No Data-- | | ∿150? |
| Upper Kau area | 19 23.7 | 155 17.3 | ∿22 | -- | -- | 100 |
| 1955 eruption area, East Rift | 19 26.5 | 154 57 | hot | --No Data-- | | ∿150? |
| Puulena area, East Rift | 19 28.3 | 154 53 | ? | --No Data-- | | ∿150? |
| IDAHO | | | | | | |
| Red River H.S. | 45 47.3 | 115 08.8 | 55 | 123 | 80 | 125 |
| Riggins H.S. | 45 24.7 | 116 28.5 | 47 | 120 | 95 | 125 |
| Burgdorf H.S. | 45 16.7 | 115 55.2 | 45 | 121 | 57 | 125 |
| Zim's (Yoghann) H.S. | 45 02.6 | 116 17.0 | 65 | 115 | 85 | 120 |
| Krigbaum H.S. | 44 58.1 | 116 11.4 | 43 | 121 | 96 | 125 |
| Starkey H.S | 44 51.2 | 116 25.8 | 56 | 108 | 70 | 115 |
| White Licks H.S. | 44 40.9 | 116 13.8 | 65 | 143 | 145 | 150 |
| Near Cove School | 44 35.0 | 116 37.7 | 70 | 120 | 78 | 125 |
| Near Deer Creek | 44 32.4 | 116 45.0 | 50 | 107 | 63 | 110 |
| Near Midvale | 44 28.3 | 116 43.9 | 28 | 128 | 243 | 135 |
| Near Midvale Airprt. | 44 28.2 | 116 45.9 | 28 | 121 | 51 | 125 |
| Hot Creek Springs | 44 38.5 | 116 02.7 | 34 | 111 | 62 | 115 |

subsurface temperatures from 90° to 150°C—Continued

| Reservoir Assumptions | | | | Comments |
|---|---|---|---|---|
| Sub-surface area $km^2$ 4/ | Thickness km 5/ | Volume $km^3$ 6/ | Heat content $10^{18}$ cal 7/ | |
| 1.5 | 1.5 | 2.25 | .2 | Nearly constant fumarolic activity, no water discharge; area may be larger. |
| 5 | 0.7 | 3.5 | .2 | Resistivity anomally drilled by N.S.F. grant to G. V. Keller, 1973; low-temperature convection system identified top at water table, ∿80°C at -490 m; bottom of convection near -1,150 m, ∿100°C, then steep gradient to basaltic magma chamber (?). |
| 2 | 2 | 4 | .3 | Steaming area; three wells drilled 1961, deepest ∿210 m, ∿113°C; NSF grant 1975 to University of Hawaii for deep test. |
| 2 | 2 | 4 | .3 | No surface manifestations; geophysical anomalies identified. |
| 1.5 | 1.5 | 2.25 | .2 | 9 springs discharging ∿130 lpm; mixing model T=190°C. |
| 1.5 | 1.5 | 2.25 | .2 | 4 springs discharging ∿190 lpm; mixing model T=220°C. |
| 1.5 | 1.5 | 2.25 | .2 | 2 springs discharging ∿610 lpm. |
| 1.5 | 1.5 | 2.25 | .1 | Discharging hot well. |
| 1.5 | 1.5 | 2.25 | .2 | 2 springs discharging 150 lpm; mixing model T=200°C. |
| 1.5 | 1.5 | 2.25 | .1 | 7 hot springs discharging 490 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | Numerous springs discharging 113 lpm; may be part of larger system including hot springs near Cove School; mixing model T=220°C. |
| 1.5 | 1.5 | 2.25 | .2 | Numerous springs discharging 1,630 lpm. |
| 1.5 | 1.5 | 2.25 | .1 | Hot springs discharging 219 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | Flowing well; may be part of single system including Deer Creek and Midvale. |
| 1.5 | 1.5 | 2.25 | .2 | Flowing well; geochemical temperatures unreliable. |
| 1.5 | 1.5 | 2.25 | .1 | Springs discharging ∿3,000 lpm; mixing model suggests 195°C. |

Table 5.—Identified hot-water convection systems with indicated

| Location | | | Temperatures °C | | | |
|---|---|---|---|---|---|---|
| Name | Latitude ° ' N | Longitude ° ' W | Surface 1/ | Geochemical $SiO_2$ 2/ | Na-K-Ca 2/ | Subsurface 3/ |
| IDAHO Con. | | | | | | |
| Molly's H.S. | 44 38.3 | 115 41.6 | 59 | 130 | 83 | 135 |
| Vulcan H.S. | 44 34.1 | 115 41.5 | 87 | 148 | 135 | 150 |
| Cabarton H.S. | 44 25 | 116 01.7 | 71 | 124 | 99 | 130 |
| Boiling Springs | 44 21.9 | 115 51.4 | 86 | 134 | 89 | 140 |
| Near Payette River | 44 05.1 | 116 03 | 80 | 148 | 139 | 150 |
| Near Grimes Pass | 44 02.8 | 115 51.1 | 55 | 110 | 74 | 115 |
| Kirkham H.S. | 44 04.3 | 115 32.6 | 65 | 118 | 79 | 120 |
| Bonneville H.S. | 44 09.5 | 115 18.4 | 85 | 138 | 142 | 145 |
| Stanley H.S. | 44 13.5 | 114 55.6 | 41 | 107 | 47 | 110 |
| Sunbeam H.S. | 44 16.1 | 114 44.9 | 76 | 133 | 130 | 140 |
| Slate Creek H.S. | 44 10.1 | 114 37.5 | 50 | 129 | 91 | 130 |
| Roystone H.S. | 43 57.2 | 116 18 | 55 | 148 | 150 | 150 |
| N.E. Boise Thermal area | 43 36.1 | 116 09.9 | 75 | 124 | 79 | 125 |
| Neinmeyer H.S. | 43 45.5 | 115 34.7 | 76 | 138 | 126 | 140 |
| Dutch Frank Springs | 43 47.7 | 115 25.5 | 65 | 120 | 72 | 125 |
| Paradise H.S. | 43 33.2 | 115 16.3 | 56 | 118 | 72 | 120 |
| Worswick H.S. | 43 33.5 | 114 47.2 | 81 | 135 | 93 | 140 |

subsurface temperatures from 90° to 150°C—Continued

| Reservoir Assumptions | | | | Comments |
|---|---|---|---|---|
| Subsurface area km² 4/ | Thickness km 5/ | Volume km³ 6/ | Heat content $10^{18}$ cal 7/ | |
| 1.5 | 1.5 | 2.25 | .2 | 7 springs discharging 76 lpm; mixing model suggests 195°C. |
| 1.5 | 1.5 | 2.25 | .2 | 13 springs discharging ∿1,900 lpm; sinter reported. |
| 1.5 | 1.5 | 2.25 | .2 | Numerous springs discharing ∿265 lpm; mixing model T = 165°C. |
| 1.5 | 1.5 | 2.25 | .2 | Numerous vents discharging ∿600 lpm and depositing minor zeolites, calcites, and mercury minerals. |
| 1.5 | 1.5 | 2.25 | .2 | One spring discharging ∿75 lpm; mixing model suggests 200°C. |
| 1.5 | 1.5 | 2.25 | .1 | Spring(s?) discharging ∿260 lpm. |
| 1.5 | 1.5 | 2.25 | .1 | Numerous springs discharging ∿950 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 8 springs and seeps discharging ∿1,900 lpm; mixing model suggests 175°C. |
| 4 | 1.5 | 6 | .3 | 6 springs discharging ∿420 lpm; southwestern of a possible 10-km line extending NE to Sunbeam; mixing T = 180°C. |
| 1.5 | 1.5 | 2.25 | .2 | Numerous vents discharging ∿1,700 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 8 springs and seeps discharging ∿700 lpm; mixing T = 210°C. |
| 2 | 1.5 | 3 | .2 | 5 springs discharging ∿75 lpm. |
| 4 | 2 | 8 | .5 | Linear zone of springs and associated thermal wells on the NE edge of Boise; used for space heating. |
| 1.5 | 1.5 | 2.25 | .2 | 13 springs discharging ∿1,300 lpm with gas, mixing model suggests 190°C. |
| 1.5 | 1.5 | 2.25 | .2 | Numerous springs, gassy, discharging ∿1,150 lpm. |
| 1.5 | 1.5 | 2.25 | .1 | Several springs. |
| 1.5 | 1.5 | 2.25 | .2 | Numerous springs discharging ∿1,750 lpm. |

Table 5.—Identified hot-water convection systems with indicated

| Name | Location |  | Temperatures °C |  |  |  |
|---|---|---|---|---|---|---|
|  | Latitude ° ' N | Longitude ° ' W | Surface | Geochemical |  | Subsurface |
|  |  |  | 1/ | 2/ $SiO_2$ | 2/ Na-K-Ca | 3/ |
| IDAHO Con. |  |  |  |  |  |  |
| Guyer H.S. | 43 40.5 | 114 24.6 | 71 | 129 | 88 | 135 |
| Clarendon H.S. | 43 33.6 | 114 24.9 | 47 | 125 | 114 | 130 |
| Hailey H.S. | 43 30.3 | 114 22.2 | 63 | 129 | 83 | 135 |
| Near Brockie Airpt | 43 32.4 | 113 30.1 | 41 | 107 | 91 | 110 |
| Elk Creek H.S. | 43 25.4 | 114 37.6 | 54 | 113 | 80 | 120 |
| Near Punkin Corner | 43 18.1 | 114 54.4 | 35 | 123 | 71 | 125 |
| Barron's H.S. | 43 18.1 | 114 54.4 | 71 | 124 | 91 | 130 |
| Near Magic Reservoir | 43 19.7 | 114 23.2 | 71 | 138 | 163 | 140 |
| Near Bennett Creek | 43 06.9 | 115 27.9 | 68 | 129 | 71 | 135 |
| Latty H.S. | 43 07.0 | 115 18.3 | 55 | 138 | 137 | 140 |
| Near Ryegrass Creek | 43 05.8 | 115 24.6 | 62 | 129 | 81 | 135 |
| Near Radio Towers | 43 02.2 | 115 27.5 | 38 | 129 | 125 | 130 |
| White Arrow H.S. | 43 02.9 | 114 57.2 | 65 | 136 | 113 | 140 |
| Near Chalk Mine | 43 02.9 | 114 55 | 47 | 133 | 98 | 140 |
| Near Clover Creek | 43 01.4 | 115 00.6 | 43 | 113 | 70 | 120 |
| Near Gravel Pits | 42 54.3 | 115 29.5 | 34 | 109 | 144 | 145 |
| Bruneau-Grandview | 42 56 | 115 56 | 84 | 138 | 93 | 145 |
| Near Banbury | 42 41.4 | 114 50 | 59 | 136 | 108 | 140 |

subsurface temperatures from 90° to 150°C—Continued

| Reservoir Assumptions | | | | Comments |
|---|---|---|---|---|
| Subsurface area km$^2$ 4/ | Thickness km 5/ | Volume km$^3$ 6/ | Heat content $10^{18}$ cal 7/ | |
| 1.5 | 1.5 | 2.25 | .2 | Numerous springs discharging ∿3,800 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | Numerous springs discharging ∿380 lpm; mixing model suggest 215°C. |
| 1.5 | 1.5 | 2.25 | .2 | Numerous springs discharging ∿265 lpm; mixing model suggests 190°C. |
| 1.5 | 1.5 | 2.25 | .1 | 1 well flowing ∿45 lpm. |
| 1.5 | 1.5 | 2.25 | .1 | 5 springs discharging ∿55 lpm. |
| 1.5 | 1.5 | 2.25 | .1 | Flowing well discharging 15 lpm; may be part of extensive system underlying a large portion of the Cames Prairie, and including Elk Creek, Barrons, and Waldrop. |
| 1.5 | 1.5 | 2.25 | .2 | Numerous springs discharging ∿120 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | One well flowing 51 lpm; mixing models indicate temperatures as high as 275°C. |
| 1.5 | 1.5 | 2.25 | .2 | Flowing well discharging ∿2,600 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | One spring; may be part of extensive system that includes Bennett Creek and Ryegrass Creek; $SiO_2$ temperature of all may be too high because of equilibration with diatomite. |
| 1.5 | 1.5 | 2.25 | .2 | Flowing well. |
| 1.5 | 1.5 | 2.25 | .2 | 1 flowing well discharging 30 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 4 springs discharging ∿3,100 lpm; mixing model indicates 200°C. |
| 1.5 | 1.5 | 2.25 | .2 | 1 flowing well. |
| 1.5 | 1.5 | 2.25 | .1 | 1 flowing well. |
| 1.5 | 1.5 | 2.25 | .2 | 1 flowing well discharging ∿8 lpm. Na-K-Ca temperature may be inaccurate carbonate deposition reported. May be diatomaceous earth at depth. |
| 2250 | 1.5 | 3375 | 263 | An extensive area with many warm and hot artesian wells; mixing model temperatures up to 275°C. |
| 8 | 1.5 | 12.0 | .9 | 1 flowing well discharging ∿225 lpm; mixing T =215°C; includes Miracle and 1 other spring. |

Table 5.—Identified hot-water convection systems with indicated

| Location | | | Temperatures °C | | | |
|---|---|---|---|---|---|---|
| Name | Latitude ° ' N | Longitude ° ' W | Surface 1/ | Geochemical 2/ $SiO_2$ | 2/ Na-K-Ca | Subsurface 3/ |
| IDAHO Con. | | | | | | |
| Near Cedar Hill | 42 24.9 | 114 18.1 | 38 | 116 | 65 | 120 |
| Near Bridger Springs | 42 28.7 | 113 37.5 | 60 | 111 | 89 | 115 |
| Oakley Warm Springs | 42 10.4 | 113 51.7 | 47 | 119 | 92 | 120 |
| Raft River thermal area | 42 06.1 | 113 22.8 | 96 | 136 | 139 | 140 |
| Maple Grove H.S. | 42 18.2 | 111 42.2 | 76 | 107 | 236 | 110 |
| Near Riverdale | 42 09.9 | 111 50.4 | 45 | 126 | 170 | 125 |
| Wayland H.S. | 42 08.2 | 111 56.9 | 77 | 126 | 270 | 130 |
| Near Newdale | 43 53.2 | 111 35.4 | 36 | 122 | 84 | 125 |
| Ashton Warm Springs | 44 05.7 | 111 27.5 | 41 | 143 | 91 | 145 |
| MONTANA | | | | | | |
| Helena (Broadwater) Hot Spring | 46 36.5 | 112 05 | 65 | 136 | 135 | 140 |
| White Sulphur Springs | 46 32.8 | 110 54.2 | 57 | 103 | 148 | 150 |
| Alhambra H.S. | 46 27 | 111 59 | 59 | 115 | 111 | 120 |
| Boulder H.S. | 46 12 | 112 05.6 | 76 | 143 | 135 | 145 |
| Gregson (Fairmont) H.S. | 46 02.6 | 112 48.4 | 74 | 128 | 126 | 130 |
| Pipestone H.S. | 45 53.8 | 112 13.9 | 61 | 115 | 113 | 120 |
| Barkels (Silver Star) H.S. | 45 41.5 | 112 17.2 | 72 | 143 | 139 | 145 |
| Norris (Hapgood) H.S. | 45 34.6 | 111 41 | 52 | 130 | 153 | 150 |
| Jardine (Big Hole or Jackson) H.S. | 45 21.8 | 113 24.7 | 58 | 104 | 148 | 150 |

subsurface temperatures from 90° to 150°C—Continued

| Reservoir Assumptions | | | | Comments |
|---|---|---|---|---|
| Subsurface area km² 4/ | Thickness km 5/ | Volume km³ 6/ | Heat content $10^{18}$ cal 7/ | |
| 6 | 1.5 | 9 | .6 | 1 flowing well discharging ∿2,050 lpm. |
| 1.5 | 1.5 | 2.25 | .1 | 1 flowing well discharging 7,900 lpm; mixing T = 150°C. |
| 1.5 | 1.5 | 2.25 | .1 | 1 spring discharging 38 lpm; mixing T = 195°C. |
| 20 | 1.5 | 30 | 2.3 | Area of flowing hot wells recently explored by ERDA; 140°C measured at depth of 1,400 m in well flowing ∿3,800 lpm. |
| 2 | 1.5 | 3 | .2 | Numerous springs discharging ∿1,300 lpm; Na-k-Ca possibly inaccurate due to deposition of carbonate. |
| 1.5 | 1.5 | 2.25 | .2 | 1 flowing well; Na-K-Ca possibly inaccurate from deposition of carbonate. |
| 5 | 1.5 | 7.5 | .5 | Numerous springs discharging ∿3,400 lpm and depositing travertine; Na-K-Ca thermometry may be inaccurate. |
| 1.5 | 1.5 | 2.25 | .2 | Flowing well. |
| 1.5 | 1.5 | 2.25 | .2 | Springs discharging ∿8 lpm from Pleistocene basalt. |
| 1.5 | 1.5 | 2.25 | .2 | 2 hot springs discharging 110 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | About 9 springs discharging ∿2,000 lpm; mixing model suggests 150°C. |
| 1.5 | 1.5 | 2.25 | .1 | About 22 springs |
| 1.5 | 1.5 | 2.25 | .2 | Many springs in two groups; siliceous sinter; large discharge. |
| 1.5 | 1.5 | 2.25 | .2 | Several springs |
| 1.5 | 1.5 | 2.25 | .1 | Several springs. |
| 1.5 | 1.5 | 2.25 | .2 | 4 springs discharging 200 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 5 springs discharging 200 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | About 100 springs ∿5,700 lpm; mixing model indicates 150°C. |

Table 5.—Identified hot-water convection systems with indicated

| Name | Location | | Temperatures °C | | | |
|---|---|---|---|---|---|---|
| | Latitude ° ' N | Longitude ° ' W | Surface 1/ | Geochemical 2/ $SiO_2$ | 2/ Na-K-Ca | Subsurface 3/ |
| NEVADA | | | | | | |
| Bog H.S. | 41 55.5 | 118 48.1 | 88 | 108 | 109 | 115 |
| Howard H.S. | 41 43.3 | 118 30.3 | 56 | 128 | 81 | 130 |
| Dyke H.S. | 41 34.0 | 118 33.7 | 66 | 129 | 137 | 140 |
| Near Soldier Meadow | 41 21.5 | 119 13.2 | 54 | 113 | 65 | 115 |
| Double H.S. | 41 03.0 | 119 02.8 | 80 | 140 | 127 | 145 |
| Near Black Rock | 40 57 | 118 58 | 90 | 148 | 116 | 150 |
| Fly Ranch H.S. | 40 52.0 | 119 20.9 | 80 | 127 | 154 | 130 |
| Butte Sprs. | 40 46 | 119 07 | 86 | 129 | 120 | 130 |
| Mineral H.S. | 41 47.3 | 114 43.3 | 60 | 127 | 129 | 130 |
| Hot Hole (Elko) | 40 49.1 | 115 46.5 | 89 | 115 | 127 | 115 |
| Near Carlin | 40 42.0 | 116 08.0 | 79 | 119 | 81 | 120 |
| Hot Sulphur Sprs. | 41 9.4 | 114 59.1 | 90 | 128 | 191 | 140 |
| Hot Springs Point | 40 24.2 | 116 31.0 | 54 | 116 | 233 | 125 |
| Walti H.S. | 39 54.1 | 116 35.2 | 72 | 117 | 78 | 120 |
| Spencer H.S. | 39 19 | 116 51 | 72 | 123 | 210 | 125 |
| Hot Pot | 40 55.3 | 117 06.5 | 58 | 125 | 195 | 125 |

subsurface temperatures from 90° to 150°C—Continued

| Reservoir Assumptions | | | | Comments |
|---|---|---|---|---|
| Subsurface area km² 4/ | Thickness km 5/ | Volume km³ 6/ | Heat content $10^{18}$ cal 7/ | |
| 2 | 2 | 4 | .2 | 2 springs discharging ∿4,000 lpm at 54°C. |
| 1.5 | 1.5 | 2.25 | .2 | Several springs. |
| 1.5 | 1.5 | 2.25 | .2 | 1 (?) spring discharging ∿100 lpm. |
| 6 | 2 | 12 | .7 | Several springs in area of ∿6 km$^2$ discharging ∿50 lpm. |
| 10 | 2 | 20 | 1.6 | Several springs along linear zone 20 km north from Black Rock Point; largest group discharging ∿175 lpm; minor travertine. |
| 1.5 | 1.5 | 2.25 | .2 | |
| 8 | 2 | 16 | 1.1 | Area of large spring pools and two abandoned wells discharging ∿500 lpm and depositing travertine, so Na-K-Ca may be too high. |
| 1.5 | 1.5 | 2.25 | .2 | |
| 1.5 | 1.5 | 2.25 | .2 | Several springs and shallow wells. |
| 2 | 1.5 | 3 | .2 | Several springs depositing travertine, so Na-K-Ca temperature may be high. |
| 1.5 | 1.5 | 2.25 | .1 | |
| 1.5 | 1.5 | 2.25 | .2 | 3 springs discharging ∿190 lpm; paleozoic limestone at depth; Na-K-Ca geothermometer may be inaccurate; may be part of more extensive area extending 4.8 km along west edge of Snake Mtns. |
| 5 | 1.5 | 7.5 | .5 | Hot springs, discharging ∿125 lpm; depositing travertine; Na-K-Ca may be inaccurate. |
| 2 | 1.5 | 3 | .2 | 6 springs discharging 300 lpm and depositing travertine. |
| 1.5 | 1.5 | 2.25 | .2 | Several hot springs discharging 50 lpm and depositing travertine so Na-K-Ca thermometry may be inaccurate. |
| 1.5 | 1.5 | 2.25 | .2 | One spring discharging ∿270 lpm; depositing travertine; Na-K-Ca may be inaccurate. |

Table 5.—Identified hot-water convection systems with indicated

| Location | | | Temperatures °C | | | |
|---|---|---|---|---|---|---|
| Name | Latitude ° ' N | Longitude ° ' W | Surface 1/ | Geochemical $SiO_2$ 2/ | Geochemical Na-K-Ca 2/ | Subsurface 3/ |
| NEVADA Con. | | | | | | |
| Buffalo Valley H.S. | 40 22.1 | 117 19.5 | 79 | 125 | 140 | 130 |
| Hot Springs | 41 25.4 | 117 23.0 | 58 | 107 | 209 | 110 |
| Golconda H.S. | 40 57.7 | 117 29.6 | 74 | 116 | 201 | 125 |
| Sou (Gilberts) H.S. | 40 05.4 | 117 43.5 | 93 | 115 | 99 | 115 |
| Dixie H.S. | 39 47.9 | 118 04.0 | 72 | 143 | 143 | 150 |
| The Needles | 40 08.8 | 119 40.5 | 98 | 137 | 214 | 145 |
| Walleys H.S. | 38 58.9 | 119 49.9 | 71 | 109 | 85 | 110 |
| Nevada H.S. | 38 54.0 | 119 24.7 | 61 | 104 | 86 | 105 |
| Darrough H.S. | 38 49.3 | 117 10.8 | 97 | 136 | 127 | 140 |
| Warm Springs | 38 11.3 | 116 22.5 | 61 | 111 | 192 | 125 |
| Bartholomae H.S. | 39 24.3 | 116 20.8 | 54 | 129 | 72 | 130 |
| NEW MEXICO | | | | | | |
| Jemez (Ojos Calientes) H.S. | 35 47 | 106 41 | 73 | 134 | 197 | 135 |
| Radium H.S. | 32 30 | 106 55.5 | 52 | 124 | 222 | 130 |
| Lower Frisco | 33 15 | 108 47 | 37 | 128 | 150 | 150 |
| Gila H.S. | 33 12 | 108 12 | 68 | 121 | 114 | 125 |

subsurface temperatures from 90° to 150°C—Continued

| Reservoir Assumptions<br>Subsurface area km² 4/ | Thickness km 5/ | Volume km³ 6/ | Heat content $10^{18}$ cal 7/ | Comments |
|---|---|---|---|---|
| 4 | 2.5 | 10 | .7 | More than 200 hot springs with largest discharging 61 lpm; in travertine area so Na-K-Ca thermometry may be inaccurate. |
| 1.5 | 1.5 | 2.25 | .1 | Discharging from travertine so Na-K-Ca thermometry may be inaccurate. |
| 1.5 | 1.5 | 2.25 | .2 | About 12 springs discharging 750 lpm and depositing manganiferous travertine; area may be considerably larger. |
| 1.5 | 1.5 | 2.25 | .1 | Several hot springs depositing travertine. |
| 2 | 1.5 | 3 | .2 | Several hot springs discharging ∿200 lpm. |
| 2 | 1.5 | 3 | .2 | Two lines of springs that have deposited travertine cones in Pyramid Lake; two wells on eastern line, 116°C at 450 and 1,800 m depth; may be considerably larger system. |
| 1.5 | 1.5 | 2.25 | .1 | Many hot springs discharging ∿75 lpm along base of recent faultscarp. |
| 1.5 | 1.5 | 2.25 | .1 | Several springs in travertine area discharging ∿200 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | Several springs and well discharging ∿350 lpm; one well 129°C at 230 m depth discharging ∿4,000 lpm; area may be considerably larger. |
| 1.5 | 1.5 | 2.25 | .2 | 2 springs. |
| 1.5 | 1.5 | 2.25 | .2 | Spring discharging ∿400 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | About 10 springs depositing travertine and discharging ∿750 lpm; Na-K-Ca probably not reliable; 9.7 km SSW of Valles Caldera. |
| 1.5 | 1.5 | 2.25 | .2 | |
| 1.5 | 1.5 | 2.25 | .2 | Discharge ∿75 lpm; Na-K-Ca probably not reliable. |
| 1.5 | 1.5 | 2.25 | .2 | Four hot springs discharging ∿3,400 lpm; area may be somewhat larger. |

Table 5.—Identified hot-water convection systems with indicated

| Location |  |  | Temperatures °C |  |  |  |
|---|---|---|---|---|---|---|
| Name | Latitude ° ' N | Longitude ° ' W | Surface 1/ | Geochemical SiO$_2$ 2/ | Geochemical Na-K-Ca 2/ | Subsurface 3/ |
| OREGON |  |  |  |  |  |  |
| Mt. Hood | 45 22.5 | 121 42.5 | 90 | --No Data-- |  | 125 |
| Carey (Austin) H.S. | 45 01.2 | 122 00.6 | 86 | 126 | 118 | 125 |
| Kahneetah H.S. | 44 51.9 | 121 12.9 | 52 | 140 | 103 | 140 |
| Breitenbush H.S. | 44 46.9 | 121 58.5 | 92 | 127 | 149 | 150 |
| Belknap H.S. | 44 11.6 | 122 03.2 | 71 | 135 | 114 | 140 |
| Klamath Falls | 42 15 | 121 45 | 74 | 136 | 130 | 120 |
| Summer Lake H.S. | 42 43.5 | 120 38.7 | 43 | 134 | 112 | 140 |
| Radium H.S. | 44 55.8 | 117 56.4 | 58 | 124 | 108 | 130 |
| Hot Lake (2) | 45 14.6 | 117 57.6 | 80 | 100 | 115 | 120 |
| Medical H.S. | 45 01.1 | 117 37.5 | 60 | 125 | 125 | 130 |
| Ritter H.S. | 44 53.7 | 119 08.6 | 41 | 119 | 92 | 125 |
| Fisher H.S. | 42 17.9 | 119 46.5 | 68 | 123 | 165 | 130 |
| Blue Mountain H.S. | 44 21.3 | 118 34.4 | 58 | 99 | 126 | 130 |
| Near Little Valley | 43 53.5 | 117 30.0 | 70 | 145 | 119 | 150 |
| Beulah H.S. | 43 56.7 | 118 08.2 | 60 | 169 | 86 | 130 |
| Near Riverside | 43 28.0 | 118 11.3 | 63 | 143 | 138 | 150 |
| Crane H.S. | 43 26.4 | 118 38.4 | 78 | 127 | 124 | 130 |
| Near Harney Lake | 43 10.9 | 119 06.2 | 68 | 133 | 130 | 135 |
| Near Trout Creek | 42 11.3 | 118 09.2 | 52 | 140 | 144 | 145 |
| Near McDermitt | 42 04.1 | 117 30.0 | 52 | 120 | 100 | 120 |

subsurface temperatures from 90° to 150°C—Continued

| Reservoir Assumptions | | | | Comments |
|---|---|---|---|---|
| Subsurface area km² 4/ | Thickness km 5/ | Volume km³ 6/ | Heat content $10^{18}$ cal 7/ | |
| 2 | 2 | 4 | .3 | Many fumaroles but not water discharge; semiactive volcano; temperatures may be higher; area may be larger. |
| 1.5 | 1.5 | 2.25 | .1 | Several hot springs in 0.1 km discharging ∿950 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | Hot spring discharging ∿200 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 40 to 60 springs in 0.1 km area discharging 3,400 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 3 springs discharging ∿300 lpm. |
| 240 | 2 | 480 | 30 | Numerous springs and shallow wells discharging from fault zones; largest spring ∿200 lpm; well temperatures 60° to 115°C used for domestic heating; large area indicated. |
| 4 | 1.5 | 6.0 | .4 | 3 springs discharging ∿75 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 2 flowing wells discharging ∿1,100 lpm. |
| 1.5 | 1.5 | 2.25 | .1 | 1 large spring pool discharging ∿1,500 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 2 springs discharging ∿200 lpm. |
| 1.5 | 1.5 | 2.25 | .1 | 1 hot spring discharging ∿130 lpm. |
| 3 | 1.5 | 4.5 | .3 | Hot spring discharging ∿70 lpm; some $H_2S$. |
| 1.5 | 1.5 | 2.25 | .2 | Several springs discharging ∿250 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | Several springs discharging ∿550 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 1 (?) spring discharging ∿50 lpm from vitric tuff so $SiO_2$ temperature may not be reliable; sinter and travertine reported. |
| 1.5 | 1.5 | 2.25 | .2 | Several springs discharging ∿200 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 2 springs discharging ∿550 lpm. |
| 3 | 1.5 | 4.5 | .3 | Spring discharging ∿550 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | Several springs discharging ∿200 lpm. |
| 2 | 1.5 | 3.0 | .2 | Hot spring discharging ∿750 lpm. |

Table 5.—Identified hot-water convection systems with indicated

| Name | Location |  | Temperatures °C |  |  |  |
|---|---|---|---|---|---|---|
|  | Latitude ° ' N | Longitude ° ' W | Surface 1/ | Geochemical $SiO_2$ 2/ | Geochemical Na-K-Ca 2/ | Subsurface 3/ |
| UTAH |  |  |  |  |  |  |
| Hooper H.S. | 41 08 | 112 11.3 | 60 | 101 | 223 | 105 |
| Crystal H.S. | 40 29 | 111 54 | 58 | 103 | 135 | 135 |
| Baker (Abraham, Crater) H.S. | 39 36.8 | 112 43.9 | 87 | 118 | 122 | 125 |
| Meadow H.S. | 38 51.8 | 112 30 | 41 | 100 | 68 | 105 |
| Monroe(Cooper) H.S. | 38 38.2 | 112 06.4 | 76 | 110 | 118 | 120 |
| Joseph H.S. | 38 36.7 | 112 11.2 | 64 | 133 | 141 | 140 |
| WASHINGTON |  |  |  |  |  |  |
| Sol Duc H.S. | 47 58.1 | 123 52.1 | 56 | 148 | 92 | 150 |
| Olympic H.S. | 47 58.9 | 123 41.2 | 52 | 126 | 87 | 130 |
| Sulphur Creek H.S. | 48 15.3 | 121 10.8 | 37 | 122 | 113 | 125 |
| Garland (San Juan) | 47 20.5 | 121 53.4 | 38 | 148 | 185 | 150 |
| Ohanapecosh H.S. | 46 44.2 | 121 33.6 | 49 | 126 | 164 | 130 |
| WYOMING |  |  |  |  |  |  |
| Huckleberry H.S. | 44 07 | 110 41 | 71 | 150 | 141 | 150 |
| Auburn H.S. | 42 49.5 | 111 0 | 62 | 143 | 209 | 150 |
| Totals (224 Systems) |  |  |  |  |  |  |

subsurface temperatures from 90° to 150°C—Continued

| Reservoir Assumptions<br>Subsurface area km² 4/ | Thickness km 5/ | Volume km³ 6/ | Heat content $10^{18}$ cal 7/ | Comments |
|---|---|---|---|---|
| 1.5 | 1.5 | 2.25 | .1 | 4 saline hot springs in 2 groups 0.6 km apart; geothermometry may not be reliable. |
| 1.5 | 1.5 | 2.25 | .2 | 4 hot springs discharging ~230 lpm. |
| 1.5 | 1.5 | 2.25 | .1 | 4 hot springs depositing travertine and Mn oxides at edge of young basalt flows. |
| 1.5 | 1.5 | 2.25 | .1 | 3 springs on 1.6 km trend; includes Hatton Hot Springs (Black Rock or Wiwepa) Hot Springs; analyzed spring discharges 226 lpm |
| 5 | 1.5 | 7.5 | .5 | 9 springs in 3 groups on 48 km trend along Sevier fault; includes Red Hill and Johnson Hot Springs; depositing travertine. |
| 1.5 | 1.5 | 2.25 | .2 | Springs depositing travertine and discharging ~110 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 11 springs discharging ~500 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | 17 springs discharging ~500 lpm along fault zone. |
| 1.5 | 1.5 | 2.25 | .1 | Springs discharging 15 lpm; minor precipitation (carbonate?). |
| 1.5 | 1.5 | 2.25 | .2 | 3 springs discharging ~95 lpm; extensive travertine; chemical temperatures not reliable. |
| 1.5 | 1.5 | 2.25 | .2 | 5 springs discharging ~225 lpm; extensive precipitation (carbonate?). |
| 1.5 | 1.5 | 2.25 | .2 | 2 small groups of hot springs discharging ~380 lpm. |
| 1.5 | 1.5 | 2.25 | .2 | More than 100 vents; discharging ~140 lpm and depositing travertine. |
| ~2938 |  | ~4564 | ~345 |  |

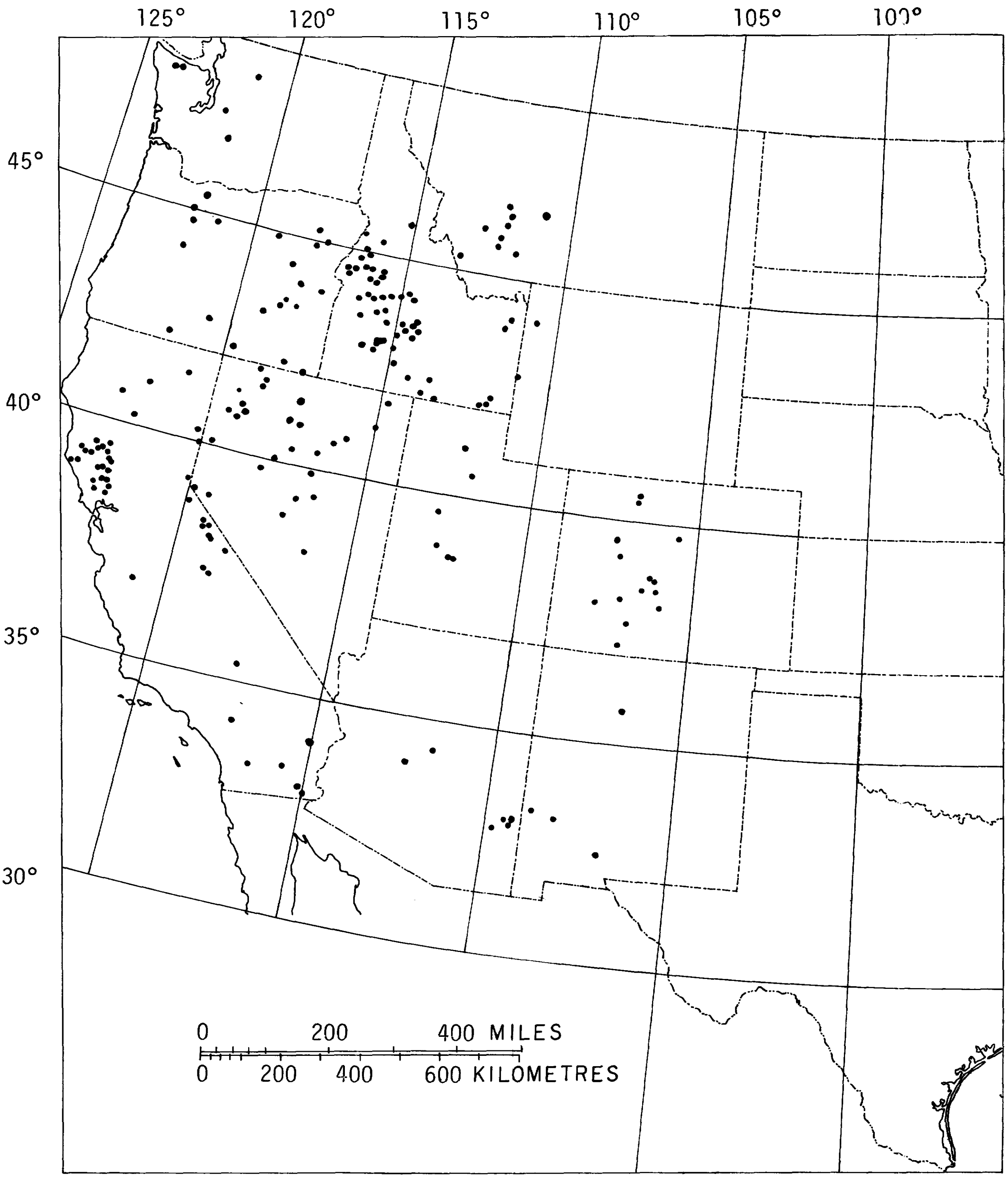

FIGURE 3.—Location of hydrothermal convection systems in the conterminous United States with indicated subsurface temperatures between 90° and 150°C.

dissolved salts (1,000 to 10,000 mg/kg), but a few contain 2 to 3 percent. The Salton Sea geothermal system is especially saline, having about 26 percent dissolved salts at reservoir temperatures exceeding 340°C.

Much attention has been given recently to constituents whose contents are strongly dependent on temperature. A few of these are useful in predicting subsurface temperatures from chemical analyses of water samples from springs or shallow wells. $SiO_2$ (Fournier and Rowe, 1966) and Na-K-Ca relations (Fournier and Truesdell, 1973) have been especially useful in providing most of the predicted temperatures in this report.

The basic assumptions involved in chemical geothermometers need to be emphasized. The most important (Fournier and others, 1974) are: (1) temperature-dependent reactions exist between constitutents in the water and the rocks of a reservoir; (2) all constituents involved in the reactions are sufficiently abundant so that supply is not a limiting factor; (3) chemical equilibrium is attained at the reservoir temperature; (4) little or no equilibration or change in composition occurs at lower temperatures as the water flows from the reservoir to the surface; and (5) the water from the reservoir does not mix with any other water at intermediate levels. Assumptions 1, 2, and 3 commonly seem to be valid for the $SiO_2$ and Na-K-Ca geothermometers. Nearly all reservoir rocks contain quartz, and residence times of a few days or weeks are sufficient to saturate the water in $SiO_2$ with respect to quartz at temperatures much above 150°C. Also, most waters seem to attain equilibrium in Na, K, and Ca with respect to the common clay minerals and feldspars. However, some indicated temperatures of our tabulated data are not reliable, at least in part because waters high in free $CO_2$ may not have attained equilibrium with the rocks or because they attained equilibrium with mineral assemblages other than those assumed for the geothermometers. In order to gain internal consistency, the $SiO_2$ temperatures reported in the tables are based on equilibrium with quartz rather than chalcedony or amorphous forms of silica. However, some reported systems, especially those of low temperature, may have equilibrated with one of these more soluble forms of silica. The predicted temperatures of such systems will be too high. Assumption 4, that water flows to the surface without chemical change, is probably never strictly true, but useful minimum temperatures can be predicted. Assumption 5, that no mixing occurs with cool shallow waters, may frequently be invalid. Mixing, formerly considered to be a major obstacle in predicting subsurface temperatures, has recently been utilized to advantage by Fournier and Truesdell (1974). In favorable circumstances, temperatures higher than those indicated by the $SiO_2$ on Na-K-Ca geothermometers can be predicted at deeper levels in a stacked series of reservoirs (Truesdell and Fournier, 1975). These mixing models are still so new that they have been applied only to a few systems. Other chemical and isotopic methods of temperature prediction are also being developed by Truesdell and others.

Experience has shown that natural geysers and active deposition of siliceous sinter are reliable indicators of subsurface temperatures at least as high as 180°C. On the other hand, travertine deposits ($CaCO_3$) and opaline residues produced by sulfuric acid leaching (from oxidation of $H_2S$) are commonly identified incorrectly as siliceous sinter but actually have no reliable relation to reservoir temperature.

The origin of the heat has major importance in predicting the geothermal resources of individual convection systems. Two principal origins are considered here: (1) heat directly related to volcanic sources localized as "hotspots" in the shallow crust of the Earth (Smith and Shaw, this circular) and (2) heat related to geothermal gradient, or the general increase in temperature with depth as a consequence of conductive heat flow (Diment and others, this circular). For both types, the ultimate source of most of the heat is from deep within the Earth, probably resulting in large part from natural radioactivity. As indicated by Smith and Shaw, the basalts and andesites that form most volcanoes have probably risen rapidly from the mantle to the surface in volcanic eruption. As a result, their heat is dispersed rather than stored and does not provide useful geothermal concentrations. However, the high-silica varieties of volcanic rocks, perhaps because of their very high viscosities, commonly are associated with magma chambers at shallow levels in the crust (perhaps 2 to 10 km but most commonly about 4 km; Smith and Shaw, this circular) and can sustain high-temperature convection systems for many thousands of years. Many large geothermal systems appear to be associated with young silicic volcanic rocks. Some hot-spring systems that have no direct association with young silicic volcanic systems may derive their heat from older volcanic systems or from very young igneous systems with no surface expression.

Other hot-spring systems are probably not related to silicic volcanic rocks. The heat of their systems is related to the regional geothermal gradient, which is higher in some regions such as the Great Basin than in others (Diment and others, this circular). Many hot springs of the Great Basin emerge from steeply dipping faults that may extend to depths of at least a few kilometres (Hose and Taylor, 1974; Olmsted and others, 1975). The water may be entirely of surface origin, circulating downward, being heated by thermal conduction with consequent decrease in density, and then rising and discharging from surface springs. In such systems, the normal conducted heat is being removed; temperatures immediately adjacent to the deep recharge channels are lower than those at similar depths not affected by convective heat losses. Temperatures should decline with time as rocks adjacent to channels are cooled and as new heat is supplied by conduction through increasing distances from channel walls. In our opinion, the abundant fault-controlled spring systems of low temperature throughout the Great Basin are likely to be of this origin. We suspect, however, that systems such as Beowawe, Leach, and Bradys in Nevada require volcanic heat and are not supplied only by geothermal gradient, even though located within the Battle Mountain high where conductive heat flow is considerably higher than the normal heat flow of the Great Basin (Diment and others, this circular). We, with R. L. Smith (oral commun. 1975), are skeptical that geothermal gradient alone can sustain high temperatures for the long durations of time indicated for these systems.

### *Identified systems*

The accompanying tables are based on the scanty data available to us early in 1975. Sixty-three systems have indicated temperatures above 150°C (table 4 and figs. 1 and 2), and 224 have indicated temperatures between 90°C and 150°C (table 5 and figs. 2 and 3). Numerous hot springs in the range of 50° to 90°C (Waring, 1965) have not been included because geochemical and other evidence is lacking to suggest reservoir temperatures greater than 90°C. As additional data become available,some of these will no doubt qualify for higher temperature categories.

The more prominent systems have well-established names from local usage and literature. In most instances the name appearing on the topographic map of the area or the name given by Waring (1965) is used. If more than one name is available locally or in the literature for a particular spring, the additional names are shown in parentheses in the tables. Other springs or wells without established names are identified by some nearby geographic feature on available maps, which also provide latitude and longitude.

Measured surface temperatures provide minimum reservoir temperatures. Where the chemical temperatures $T_{SiO_2}$ and $T_{Na\text{-}K\text{-}Ca}$ both indicate temperatures above about 125°C, we are confident that most subsurface temperatures will equal or exceed the predicted temperature. The user of these tables, however, should be especially skeptical of temperatures that are below 125°C, as well as temperatures that differ between the two chemical methods by more than about 20°C. Other systems whose predicted temperatures warrant skepticism are those of moderately high discharge (more than about 50 lpm from a single spring or obout 200 lpm from a system) that also have surface temperatures much below boiling (70°C or less). An indicated high subsurface temperature is credible for a cool spring of low discharge where excess heat can be lost by conduction but is much less credible for a system combining a low surface temperature and a high rate of discharge. Geochemical temperatures in most but not all cases provide minimal estimates of subsurface temperatures. Note that we have predicted some reservoir temperatures that are near the average rather than the maximum geochemical temperature. In most cases, our predicted temperature is at least as high as the preferred geochemical temperature (generally $T_{SiO_2}$); however, in some systems where subsurface temperature projections have been made (most notably by Olmsted and others, 1975), the assumed reservoir volume includes a substantial part that may be less than the indicated geochemical temperature.

The subsurface area assumed to be underlain by a reservoir of the indicated average temperature is derived from all available data. These include, as minimum, the surface area containing springs, spring deposits, and bleaching from attack by sulfuric acid derived from oxidation of $H_2S$. Geophysical data (Combs and Muffler, 1973), where available, provided the principal means for estimating the area and, in a few cases, the indicated depth of the reservoir, even though sufficient drilling has not yet been done to document carefully the relation between a geophysical anomaly and geothermal potential. Parts or all of some electrical resistivity anomalies may be caused by hydrothermal alteration, rocks rich in clay minerals, or saline ground waters, particularly in many areas of the Basin and Range province. Other types of geophysical surveys may also indicate anomalies that are not closely related to geothermal reservoirs. In most instances where surface expression and geology were used to indicate reservoir dimensions and geophysical data were then examined, the reservoir dimensions either remained the same or, more commonly, were significantly increased.

Although the pattern of industry exploration and drilling activity is viewed as highly significant in indicating the extent of a reservoir in several areas, in general only scanty data are available now from private industry. The lack of reliable data concerning areal extent is a serious constraint in this assessment because many estimates of the subsurface areas shown in tables 3 to 5 differ by more than three orders of magnitude; in contrast, all other parameters vary by less than one order of magnitude. Thus, the areal extent is the most critical single parameter in estimating the heat content of a system. Temperature, however, is of critical importance in determining how a system may be utilized. Systems with minimal surface evidence, such as a single spring, a restricted group of springs, or a single thermal well without other evidence, and systems for which geology or geophysics do not suggest a larger subsurface area are arbitrarily assigned a subsurface area of 1.5 km² (assumed to be 1½ km long on the dominant structural trend, even if unknown in direction, and 0.5 km on each side of this trend). Many of the separate systems we have indicated may be interconnected at depths greater than 2 or 3 km.

The heat reservoir of all convection systems is arbitrarily assumed to extend to 3 km in depth, which is the current limit of geothermal drilling. Heat at greater depths in volcanic systems is included in the volcanic system resources (Smith and Shaw, this circular); heat below 3 km in depth in other areas is included in the resource base calculations for conduction-dominated regions (Diment and others, this circular). A convection system in the latter environment has removed heat, relative to surrounding ground, as previously noted.

The top of a convective reservoir is generally not well defined but is generally assumed to have an average depth of 1, 1 ½, or 2 km, depending on assumed shape of the convection system and inferred similarities to drilled areas. Although the differences among our various depth estimates (tables 3 to 5) clearly affect drilling costs, the tables show that assumed thickness introduces much less variation in calculated volumes and heat contents than the assumed areas.

The tabulated volumes are simple multiplications of the assumed areas and thicknesses. Estimated stored heat is then calculated from reservoir temperatures (less 15°C, ambient surface temperature; for simplicity, assumed constant for all of the United States), volume, and volumetric specific heat assumed as 0.6 cal/cm³°C. Volumetric specific heats are known to differ slightly by rock type, porosity, and water content (Diment and others, this circular), but the assumption of a single volumetric specific heat introduces only slight errors relative to the great uncertainties of other parameters.

Little is known about the specific intermediate-temperature systems of table 5 and figures 2 and 3. Most of these systems are included in this category because of their chemically indicated temperatures but are listed with minimal reservoir areas, volumes, and heat contents. One notable exception is the Bruneau-Grandview area of Idaho, shown on table 5 as having an area of 2,250 km² and $263 \times 10^{18}$ cal of stored heat. This large area in the southwestern part of the Snake River Plain is characterized by hot springs of modest temperature (commonly 35° to 45°C; Waring, 1965) and many shallow thermal wells that discharge at temperatures as high as 84°C. In addition to this broad distribution of thermal springs and wells, the regional heat flow is probably high to very high (Diment and others, this circular), and geophysical surveys show no sharp boundaries for the area known to be anomalous. This geothermal area is likely to be huge, and it may even extend under a large part of the Snake River Plain.

Even less is known about our low-temperature hydrothermal resources (<90°C). Many spring systems tabulated by Waring (1965) are probably in this category, and the warmer ones may be useful in space heating. For example, Iceland and Hungary make extensive use of water at temperatures below 100°C, and 80°C is actually the preferred distribution temperature in Reykjavik, Iceland (Einarsson, 1970).

### *Pattern of distribution of identified convection systems*

Figures 1 and 3 confirm the well-known abundance of thermal systems in the Western United States and their scarcity elsewhere. Most of the high-temperature systems occur in the areas of anomalously high conductive heat flow (Diment and others, this circular, figs. 9 to 11); many of these systems also occur in or near areas of young volcanic rocks (Smith and Shaw, this circular, figs. 5 to 7).

The numerical data of tables 4 and 5 are summarized in table 6, which also divides the systems into two categories, depending on whether the predicted magnitude of their heat reservoirs exceeds the minimum assumed value.

Note that the heat contained in identified hot-water systems is about 30 times that in vapor-dominated systems, and total heat contained in systems with indicated temperatures above 150°C is about the same as that in systems between 90°C and 150°C. Such comparisons of systems of different types must be tempered by the extent of our knowledge of each type; for obvious reasons, much more attention has been given to the more attractive large high-temperature systems. Six of the high-temperature systems (Surprise Valley, Long Valley, Coso Hot Springs, Salton Sea, and Heber, California, and Yellowstone National Park, Wyoming) are each predicted to contain more than $10 \times 10^{18}$ cal of stored heat; they total about 75 percent of the total estimated heat of all of the identified high-temperature systems. Even more striking is the dominance of a few large systems in the intermediate-temperature range. Only two identified systems are predicted to contain more than $10 \times 10^{18}$ cal each, and only seven contain more than $1 \times 10^{18}$ cal. The dominance of the Bruneau-Grandview area of Idaho is especially startling; this may be more a reflection of a lack of adequate data and reliable predictive technique than of fact. However, geothermal convection systems may have the same log-normal relation between grade and frequency that metalliferous deposits and hydrocarbon reservoirs have. If this is so, relatively few systems contain most of the resources.

### *Undiscovered convective systems*

Good reasons exist for optimism that abundant geothermal resources in hot-water convective systems are available for future discovery. Our use of the term "discovery," however, must be defined; a geothermal discovery is considered to result from any of the following:

1. New knowledge of the extent of an already identified system that increases its tabulated volume appreciably; the difference is considered to be the newly discovered part (but this may be offset in part by decreased estimates for individual systems).
2. The temperature of an identified system is found to be higher than first estimated—enough for the system to qualify for a higher temperature category and more valued potential utilization (but increases may also be offset, probably in small part, by decreases).
3. A previously unknown system is discovered, commonly with no obvious surface evidence for its existence.

Most of the tabulated convection systems of this report (tables 4 and 5) should be viewed as targets for future exploration and discovery.

Our reasons for being optimistic that many exploitable hot-water systems exist for future discovery are:

1. Many of the young silicic volcanic systems tabluated by Smith and Shaw (this circular) have no recognized convection systems.
2. Other young silicic systems may still be developing, with no direct evidence for their existence in the shallow crust.
3. With few exceptions, old, deeply eroded volcanic systems are associated with exten-

**Table 6.—Summary of identified hydrothermal convection systems**

| | Number | Subsurface area, km$^2$ | Volume, km$^3$ | Heat Content, $10^{18}$ cal |
|---|---|---|---|---|
| Vapor-dominated systems (∿240°C) | 3 | 122 | 194 | 26 |
| Hot-water systems, identified | | | | |
| High-temperature systems (<150°C) | | | | |
| Systems each with heat content $>0.2 \times 10^{18}$ cal | 38 | 1374 | 2939 | 366 |
| Systems each with heat content $\leq 0.2 \times 10^{18}$ cal | 25 | 40 | 56 | 5 |
| Total high-temperature systems | 63 | 1414 | 2995 | 371 |
| Intermediate-temperature systems (90°-150°C) | | | | |
| Systems each with heat content $>0.2 \times 10^{18}$ cal | 28 | 2638 | 4112 | 311 |
| Systems each with heat content $\leq 0.2 \times 10^{18}$ cal | 196 | 300 | 452 | 34 |
| Total intermediate-temperature system | 224 | 2938 | 4564 | 345 |
| Total identified hot-water systems | 287 | 4352 | 7559 | 714 |
| Total hydrothermal convection systems | 290 | 4474 | 7753 | 740 |

sive hydrothermal alteration. Until recently, such alteration was interpreted as the effect of magmatic fluids, perhaps much different from the large convection systems of Larderello, The Geysers, Wairakei, and the Imperial Valley fields. However, extensive isotope studies of waters and rocks of both the old and the presently active systems have shown that local waters of surface origin are generally the dominant fluid (Taylor, 1974; White, 1974); the active systems are probably the present-day equivalents of old ore-forming systems. The volumes of altered rocks of the ore-forming systems are commonly many tens or hundreds of cubic kilometres. Furthermore, the isotope studies also demonstrate that each volume of altered rock commonly required the flow of 1 to 10 volumes of water through the system. The isotopic and other data also indicate that temperatures of these old systems most frequently ranged from 200° to 400° C at probable depths of 1 to 4 km below the ground surface of the time. If this analogy is correct, many active systems should have similar volumes and temperatures in their deeper parts.

4. Many old volcanic systems probably still sustain moderate- to high-temperature convection systems that may not have surface expression. Most of these volcanic systems are too old or poorly known to be evaluated in detail (Smith and Shaw, this circular).
5. Recent major progress has been made in applying several kinds of chemical, isotopic, and thermodynamic mixing models to convection systems that differ from the simple model (Fournier and Truesdell, 1974; Truesdell and Fournier, 1975). Different levels of mixing with dilute, cool meteoric waters are probably involved. With proper sampling of springs and shallow wells, evidence for high temperatures at deeper levels can be obtained; such evidence is normally lost by re-equilibration in a hot reservoir of a simple system. Reassessment of data from many of the systems of tables 4 and 5 and from other inconspicuous systems of low surface temperature is likely to result in many new discoveries, as we have defined the term.

We are fully aware that some extensively explored areas are better known to some others than to us, especially in light of the recent rapid rate of accumulation of proprietary data by industry. In time, some of these data will become available, and our techniques, estimates, and assumptions will improve enough to justify a new assessment.

We estimate that five times the volume and heat contents of the high- temperature (>150°C) systems of table 4 (excluding Yellowstone Park) are not presently recognized and exist as targets for future discovery. We cannot specifically justify this number other than to emphasize our previously stated reasons for optimism; a factor of 2 is almost certainly too small, and 20 is likely to be too large. We estimate that about three times the volume and heat content of the intermediate-temperature resources of table 5 are unrecognized, but this may be conservative.

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