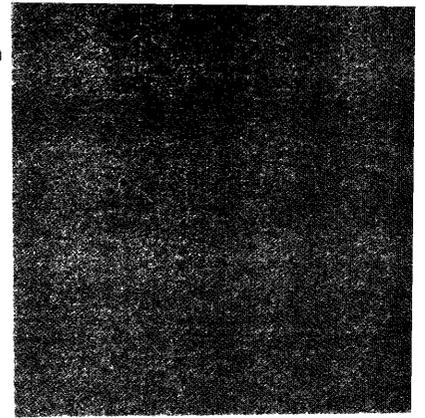


Geothermal Resources in the Banbury Hot Springs Area, Twin Falls County, Idaho



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Water-Supply
Paper 2186

Prepared in
cooperation with the
U.S. Department
of Energy



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By R. E. LEWIS and H. W. YOUNG

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CONTENTS

Abstract	1
Introduction	1
Purpose and approach	1
Previous investigations	2
Acknowledgments	4
Well- and spring-numbering system	4
Geology	4
Hydrology of the geothermal system	4
Occurrence and movement	4
Depth of circulation	6
Fluctuations in discharge and artesian head	8
Water chemistry	8
Chemical character	8
Chemical geothermometers	8
Isotopes	11
Tritium	14
Deuterium and oxygen-18	17
Thermal ground-water discharge and associated convective heat flux	21
Areal extent of the geothermal reservoir	22
Summary	23
Selected references	26
Metric conversion factors	27

FIGURES

1. Map showing generalized geology of the Banbury Hot Springs area	2
2. Diagram showing well- and spring-numbering system	5
3. Map showing potentiometric-surface contours and well and spring locations, Banbury Hot Springs	10
4. Hydrograph of discharge from well 9S-14E-4CDB1	12
5. Hydrograph of water levels in well 9S-14E-4BBD1	13
6. Comparison of reservoir temperatures estimated by the silica and sodium-potassium-calcium geothermometers	17
7. Relation of tritium concentration to residence time, assuming piston-flow and well-mixed ground-water systems in Yellowstone National Park	18
8. Relation between concentrations of deuterium and oxygen-18	19
9. Relation of chloride to deuterium	21
10. Relation of chloride to enthalpy	21
11. Relation of chloride to oxygen-18	21
12. Relation of chloride to fluoride	22
13. Map showing approximate proven and potential areas of low-temperature geothermal water	24

TABLES

1. Records of wells	7
2. Chemical analyses of water from selected wells and springs	14
3. Estimated reservoir temperatures and free energy of formation for selected thermal wells and springs	16
4. Concentrations of tritium in water sampled from selected thermal wells and springs	16
5. Stable-isotope analyses of water sampled from selected wells and springs	20

Geothermal Resources in the Banbury Hot Springs Area, Twin Falls County, Idaho

BY R. E. LEWIS AND H. W. YOUNG

Abstract

Thermal water 30.0 degrees to 72.0 degrees Celsius is produced from 26 wells and 2 springs in the vicinity of Banbury Hot Springs near Buhl, Idaho. Thermal water is used for residence heating, catfish and tropical fish production, greenhouse operation, swimming pools, and therapeutic baths. In 1979, 10,300 acre-feet of thermal water was utilized; heat discharged convectively from the geothermal system was about 1.1×10^7 calories per second. Decline in artesian head and discharge apparent in recorder charts from two wells may represent seasonal fluctuations or may reflect reservoir response to development of the resource.

The thermal waters sampled are sodium carbonate or bicarbonate in character and slightly alkaline. Mixing of hot (72 degrees Celsius) water with local cooler ground water can be shown from various relations among stable isotopes, chloride, and enthalpy. On the basis of concentration of tritium, the age of most of the water sampled is at least 100 years and perhaps more than 1,000 years. Some water (33 degrees Celsius) may be as young as 29 years. On the basis of silica, sodium-potassium-calcium, and sulfate-water geothermometers, the best estimate of the maximum reservoir temperature for the thermal water is between 70 degrees and 100 degrees Celsius.

INTRODUCTION

The Banbury Hot Springs area, as discussed in this report, is located immediately south of the Snake River between Salmon Falls Creek and Deep Creek in Twin Falls County, south-central Idaho (fig. 1). Thermal water issuing from springs and several shallow wells has been used for many years in swimming pools and therapeutic baths.

In the early 1970's, several wells that produce thermal water were drilled. Successful use of these wells led to increased development of the resource. At present, 26 wells that produce thermal water have been completed. Water from these wells flows at land surface and is used for residence heating, catfish and tropical fish production, and greenhouse operation.

Due to the increasing number of wells being completed, many residents are concerned that continued development may decrease the amount of geothermal water available to present users. If continued development

reduces flow or causes heads to drop below land surface, the economic advantage of using the resource would be greatly impaired. Therefore, to aid in future decisions regarding development and use of the resource, the U.S. Geological Survey, in cooperation with the U.S. Department of Energy, undertook this study of the nature and occurrence of geothermal water in the Banbury Hot Springs area.

Purpose and Approach

The overall purpose of this study was to define the nature and extent of the geothermal reservoir in the Banbury Hot Springs area. Specific objectives were to (1) inventory selected wells and springs in the area and determine the present (1979) quantity of thermal water being used, (2) define boundaries of the geothermal reservoir, (3) evaluate the existing resource as to its temperature and pressure at land surface and its chemical character, and (4) estimate reservoir temperatures by using chemical geothermometers.

The approach used in the study included (1) inventory of 50 thermal and nonthermal wells and 2 thermal springs in the Banbury Hot Springs area, (2) collection of water-level, or pressure, and discharge measurements where possible at the time of inventory, (3) collection of water samples from 21 thermal wells and 2 thermal springs for chemical analyses, including common ions, silica, and the minor elements of arsenic, boron, lithium, and mercury, and (4) collection of water samples from nine wells and two springs for deuterium and oxygen-18 analyses, four wells and one spring for tritium analyses, and two wells and one spring for sulfate-water isotope analyses.

Water-level measurements were used to compile a generalized potentiometric map. Discharge measurements and water temperatures at land surface were used to determine the present quantity of thermal water being utilized and the associated convective heat flux. Reservoir temperatures were estimated for all sampled thermal water in the Banbury Hot Springs area and for selected thermal water in the nearby areas using the silica and Na-K-Ca (sodium-potassium-calcium) geothermometers. Reservoir temperatures for two wells and one spring were estimated by using the sulfate-water isotope geothermometer. Relations of selected chemical constituents

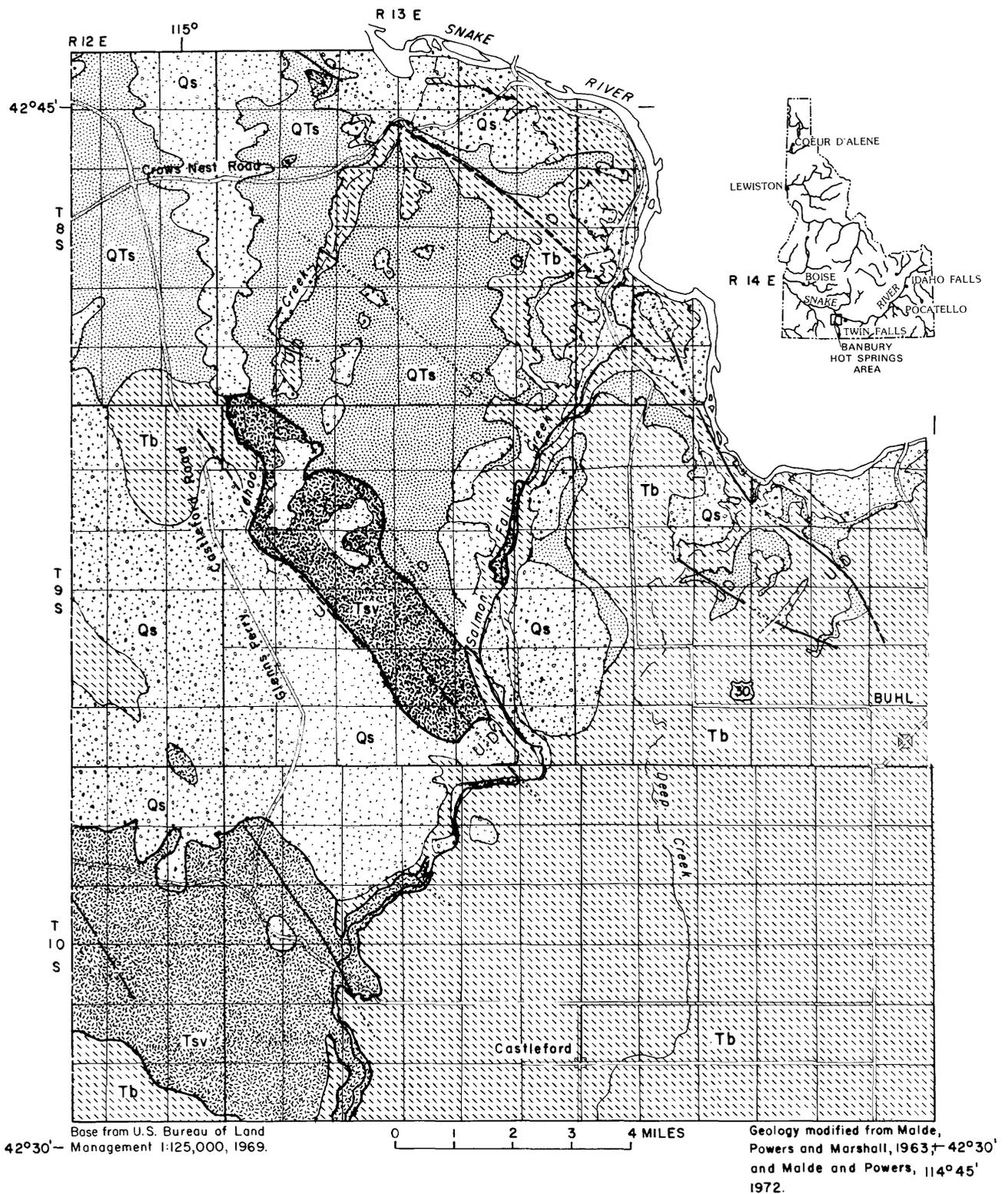


Figure 1. Generalized geology

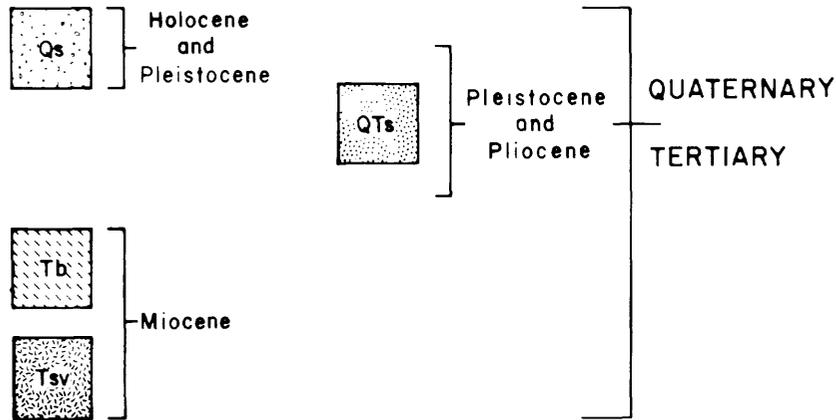
to deuterium and oxygen-18 isotopes and concentrations of tritium were used to distinguish and define the approximate areal extent of the Banbury Hot Springs geothermal reservoir.

2 Geothermal Resources, Banbury Hot Springs Area, Idaho

Previous Investigations

The occurrence of thermal water in the Banbury Hot Springs area was first mentioned in the literature by

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS



QUATERNARY SEDIMENTARY ROCKS - Chiefly terrace deposits of boulders, cobbles, and pebbles of basalt of the Melon Gravel. Includes the Tuana Gravel and surficial deposits of clay, silt, sand, and gravel. Maximum thickness probably does not exceed 300 feet



QUATERNARY AND TERTIARY SEDIMENTARY ROCKS - Poorly sorted detrital basin-fill deposits consisting of clay, silt, sand, and gravel. Chiefly lake and stream deposits of the Glenss Ferry Formation. Also include some sedimentary deposits of the Banbury Basalt. Maximum thickness is nearly 2,000 feet



TERTIARY BASALT - Chiefly lava flows of olivine basalt of the Banbury Basalt. Locally interbedded with minor amounts of stream and lake deposits. Upper basalts are generally columnar flows as much as 50 feet thick. Lower basalts are mostly vesicular, and flows are less than 15 feet thick. Maximum thickness exceeds 650 feet



TERTIARY SILICIC VOLCANICS - Chiefly thick layers of devitrified welded tuff and some bedded vitric tuff and lava flows of the Idavada Volcanics. Maximum thickness exceeds 600 feet.

— ····· Fault - Dashed where approximately located; dotted where concealed. U, upthrown side; D, downthrown side

———— Contact

of the Banbury Hot Springs area.

Stearns, Stearns, and Waring (1937). Ross (1971) summarized existing data that included several chemical analyses for the area. On the basis of similar water chemistry, Schoen (1972) concluded that granitic rocks similar

in composition to the Idaho batholith underlie the Banbury Hot Springs area. Young and Mitchell (1973) included chemical analyses from one thermal well and one thermal spring in their assessment of Idaho's geothermal

potential. Using chemical geothermometers, Young and Mitchell estimated reservoir temperatures in the study area to range from 85° to 135°C. Malde, Powers, and Marshall (1963) included the Banbury Hot Springs area in their reconnaissance geologic mapping of the west-central Snake River Plain. More detailed geologic mapping was done by Malde and Powers (1972) in their study of the Glens Ferry–Hagerman area.

Acknowledgments

Many landowners in the Banbury Hot Springs and nearby areas cooperated fully in this study by allowing access to their property, supplying information about their wells and springs, and permitting water-level and discharge measurements to be made. Special thanks are due to Messrs. Leo Ray and Dick Kaster, who permitted the installation of continuous-recording equipment on their wells. The following Geological Survey employees contributed significantly to this investigation: A. H. Truesdell and N. L. Nehring provided sulfate-water isotope analyses, R. H. Mariner aided in interpretation of geochemical data, and T. A. Wyerman provided tritium isotope analyses. To all the above, the authors are grateful.

Well- and Spring-Numbering System

The well- and spring-numbering system (fig. 2) used by the U.S. Geological Survey in Idaho indicates the location of wells or springs within the official rectangular subdivision of the public lands, with reference to the Boise base line and meridian. The first two segments of the number designate the township and range. The third segment gives the section number, which is followed by three letters and a numeral to indicate the $\frac{1}{4}$ section (160-acre tract), the $\frac{1}{4}$ - $\frac{1}{4}$ section (40-acre tract), the $\frac{1}{4}$ - $\frac{1}{4}$ - $\frac{1}{4}$ section (10-acre tract), and the serial number of the well within the tract, respectively. Quarter sections are lettered A, B, C, and D in counterclockwise order from the northeast quarter of each section. Within quarter sections, 40-acre and 10-acre tracts are lettered in the same manner. Well 9S-14E-4BBD1 is in the SE $\frac{1}{4}$ NW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 4, T. 9 S., R. 14 E., and was the first well inventoried in that tract. Springs are designated by the letter "S" following the last numeral; for example, 8S-14E-31ACB1S. Wells and springs in Nevada are located in the same manner with reference to the Mount Diablo base line and meridian.

GEOLOGY

Rocks underlying the Banbury Hot Springs area are of volcanic and sedimentary origin and range in age from

late Miocene to Holocene. For purposes of this report, they are divided into the following units: (1) Tertiary silicic volcanics, (2) Tertiary basalt, (3) Quaternary and Tertiary sedimentary rocks, and (4) Quaternary sedimentary rocks. Areal distribution and descriptions of these units are shown in figure 1.

Tertiary silicic volcanics consist chiefly of welded tuff of the Idavada Volcanics of late Miocene age and are exposed locally in the canyon of Salmon Falls Creek and in the uplands southwest of the Banbury Hot Springs area. Drillers' logs indicate that this unit is widespread in the subsurface. Total thickness of the Idavada Volcanics in the vicinity of Banbury Hot Springs exceeds 2,000 ft (Malde and Powers, 1972).

Tertiary basalt, consisting chiefly of olivine basalt flows of the Banbury Basalt of late Miocene age, is the predominant rock unit in the area. This unit, reported to be about 650 ft thick, is exposed throughout the area and, as reported by drillers' logs, underlies most of the surrounding region.

Quaternary and Tertiary sedimentary rocks, consisting chiefly of detrital basin-fill deposits of the Glens Ferry Formation of late Pliocene and early Pleistocene age, are also exposed throughout the area.

Quaternary sedimentary rocks consist chiefly of surficial deposits of sand and gravel of fluvial origin. This unit includes the Melon and Tuana Gravels of late and early Pleistocene age, respectively.

Several northwest-trending normal faults have been mapped in the study area (fig. 1). Most faults have their downthrown side on the northeast. Some graben-and-horst structures occur southwest of the study area. Most of the faulting probably occurred in late Miocene time, although some faulting continued through Pleistocene time.

HYDROLOGY OF THE GEOTHERMAL SYSTEM

Occurrence and Movement

Temperatures of thermal ground water from flowing wells and springs in the Banbury Hot Springs area range from 30° to 72°C. The thermal water occurs under artesian conditions, chiefly in the Banbury Basalt and Idavada Volcanics of late Miocene age. The low concentration of magnesium in the thermal water seems to favor the Idavada Volcanics as the principal reservoir rock. Drillers' logs indicate that water also occurs in the interbedded sedimentary rocks. Locations of wells and springs in and near the study area are shown in figure 3. Well data are given in table 1.

Most wells in the study area were drilled near the Snake River northward from Deep Creek to the site of the

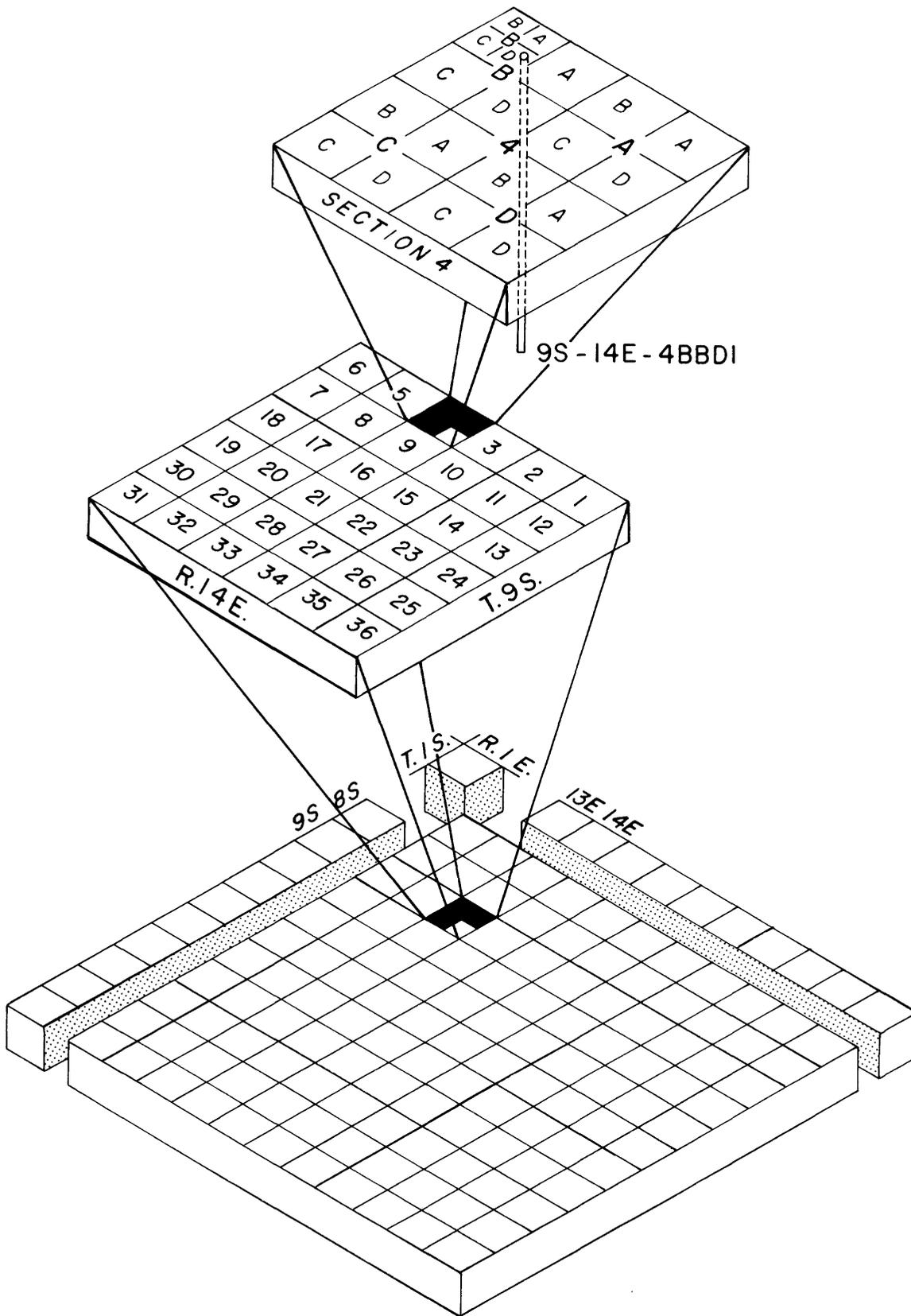


Figure 2. Well- and spring-numbering system.

Banbury Hot Springs Natatorium in the southwest quarter of section 33, T. 8 S., R. 14 E. (fig. 3). Pertinent sections in figure 3 can be recognized by the first part of the well numbers. Well depths range from 850 ft near Deep Creek to 110 ft at the natatorium. Ground-water temperatures increase northward and range from 31.5°C near Deep Creek to 59°C at the natatorium.

Thermal ground water also occurs along Salmon Falls Creek near its confluence with the Snake River (see fig. 3). Two springs and several wells discharge thermal water at temperatures ranging from 57° to 72°C. Well depths range from 420 to 700 ft in the vicinity of Salmon Falls Creek.

Temperatures of ground water in nearby areas southeast and southwest of the Banbury Hot Springs area range from 24.5° to 30.0°C in wells 350 to 900 ft deep. This water, although probably classified as thermal by most definitions, is considered part of the regional ground-water system and is not discussed in detail in this report.

Artesian heads, calculated using well-head pressure, range from a few feet to as much as 360 ft above land surface. Lack of a uniform gradient in the calculated artesian heads is probably due, in part, to the method of obtaining the pressure measurement. Artesian head determinations for some wells were obtained from pressure gages on the wells, and several readings were taken from wells that were partly shut in. Thermoartesian effects were not considered due to the questionable accuracy of some pressure measurements. Calculated heads are generally lower, however, from Deep Creek northward to the natatorium, where the potentiometric surface declines from about 3,170 to 3,080 ft above NGVD (National Geodetic Vertical Datum of 1929). Artesian heads in wells near Salmon Falls Creek are fairly uniform and range from about 247 to 262 ft above land surface. The potentiometric surface is about 3,160 ft above NGVD.

Several wells southeast and southwest of the study area also yield thermal water. To the southeast, wells 9S-14E-13DDD1 and 9S-14E-23ABD1 (see fig. 3) yield water having temperatures at the surface of 26° and 25°C, respectively. Heads calculated from pressure measurements in these wells are 4 and 29 ft above land surface, respectively, and indicate a potentiometric surface about 3,520 and 3,370 ft above NGVD, respectively. Southwest of the study area, water temperatures range between 24.5° and 30.0°C. Water levels measured in seven wells are between 259 and 449 ft below land surface. The potentiometric surface in these wells is about 3,365 ft above NGVD and is relatively flat.

On the basis of measurements made in spring 1979, a potentiometric contour map was constructed for the area south and southwest of the Banbury Hot Springs area (fig. 3). The contours are generalized and, as drawn, show possible barrier effects and compartmentalization that

could result from northwest-trending faults in the area. The inferred direction of ground-water movement is down the hydraulic gradient, which is approximately perpendicular to the potentiometric contours.

Several directions of movement and compartmented units are implied by the generalized potentiometric contours. In the southeastern part of the area depicted in figure 3, east of Salmon Falls Creek, nonthermal ground water moves in a general northwest direction. Near Salmon Falls Creek, however, where temperature and water-level data are lacking, two northwest-trending echelon faults may act as barriers and divert the non-thermal water from the Banbury area. Some of the water probably moves northeastward across the faults and may represent local cooler ground water which, it is proposed, mixes in varying proportions with the 72°C water to produce the Banbury thermal waters. Some recharge to these local cooler ground waters may occur from seepage losses along the lower reach of Salmon Falls Creek. However, absence of significant tritium in the mixed Banbury thermal waters indicates that either the component of young (less than 100 years) water is extremely small or that the ground-water velocity in the aquifer in that area is low.

Southwest of the Banbury area and west of Salmon Falls Creek, the effect of structure on ground-water movement is unclear. Generally, the potentiometric surface is relatively flat, and direction of movement is probably northward.

Depth of Circulation

Depths to which ground water circulates and becomes heated in the Banbury system cannot be determined precisely from available data. By assuming values for conductive heat flow and thermal conductivity of the rocks, however, an estimate for the depth of circulation can be obtained that is probably valid within the constraints applied.

D. D. Blackwell (unpublished data) indicated heat-flow values of 1.7 HFU (heat-flow units; 1 HFU = 10⁻⁶ cal/(cm²·s) near the south edge of the Snake River Plain. Average thermal conductivity values of 3.0, 4.0, and 4.5 mcal/(cm s·°C) for basalt, rhyolite, and sedimentary rocks, respectively, weighted for a typical drill hole in the Banbury area, result in a weighted average thermal conductivity of 3.85 mcal/(cm s·°C). Substituting values for heat flow and thermal conductivity in the conductive heat-flow equation,

$$Q = K dt/dz,$$

where

- Q = conductive heat flow,
- K = thermal conductivity, and
- dt/dz = thermal gradient,

and assuming a mean annual surface temperature of

Table 1. Records of wells

Altitude: From U.S. Geological Survey topographic maps.

Well finish: X, open hole.

Water level: F, flowing, partially shut in; P, pumping; R, reported.

Discharge: P, pumping; E, estimated.

Temperature: R, reported.

Use of water: A, air conditioning; H, domestic; I, irrigation; P, public supply; R, recreation; S, stock (catfish); U, unused.

Remarks: DL, driller's log; WQ, water-quality analysis available (table 2).

Notation: --, no data available.

Well number	Altitude of land surface (feet above National Geodetic Vertical Datum of 1929)	Reported depth of well (feet below land surface)	Casing			Water level			Discharge (gal/min) flowing, unless otherwise indicated	Temperature of water (°C)	Use of water	Remarks
			Diameter (in)	Feet below land surface to first perforation	Well finish	Feet above (+) or below land surface	Date measured					
8S-12E-24CCC1	3,480	500	12	46	X	240.08	3- 6-79	---	---	I	DL	
8S-13E-23CCD1	3,390	---	--	---	--	69.28	2-22-79	---	---	H		
35ACD1	3,479	700	16	170	X	182.43	3- 8-79	---	---	U	DL	
8S-14E-19DAD1	2,900	700	8	216	X	---	10-22-79	1	30.0	U	DL	
30ACD2	2,894	420	8	75	X	---	8-15-79	120	72.0	U	DL WQ	
30DAD1	2,900	700	6	501	X	247+ F	3-26-79	9	62.0	A	DL WQ	
30DBA1	2,896	450	8	90	X	262+	8-16-79	650	71.5	U	DL WQ	
30DBD1	2,900	450	8	147	X	262+	8-16-79	590	67.0	U	DL	
32DAA1	2,960	545	6	449	X	180+	8-15-79	10	45.5	A	DL WQ	
32DDC1	2,950	553	8	230	X	71+ F	4- 4-79	170	42.5	A	DL WQ	
33BCA1	2,910	653	10	---	--	5+ R	10-28-79	5	29.5 R	U	DL	
33BCD1	2,895	270	10	---	--	---	4- 4-79	60 P	49.0 R	R		
33CBA1	2,902	110	6	---	--	---	2- 8-78	60	59.0	R	WQ	
33CBA2	2,902	342	8	122	X	47+ F	4- 5-79	---	59.0	R	DL WQ	
33CBA3	2,902	243	6	---	--	---	----	---	59.0	R		
33CBD1	2,890	540	6	52	X	193+	3-15-79	4	42.0	A	DL WQ	
33CCA1	2,908	510	6	210	X	82+ F	3-15-79	80	44.5	A	DL WQ	
33CCC1	2,910	480	6	420	X	82+ F	3-26-79	12	30.0	A	DL WQ	
9S-12E-35BCD1	3,705	797	16	462	X	343.14	2-21-79	---	---	I	DL	
9S-13E-20CCD1	3,805	920	20	165	X	448.88	3-27-79	---	---	I	DL	
22DDD1	3,700	575	6	46	X	417.43 P	3- 6-79	---	---	H	DL	
25ADD1	3,680	400	16	129.5	X	175.80	3- 8-79	---	---	I	DL	
31DDC1	3,819	840	16	402	X	458.89	3- 6-79	---	---	I	DL	
9S-14E-4BBD1	2,938	700	6	215	X	155+ F	4-25-79	30	39.5	U	DL	
4BDC1	2,940	375	8	28	X	145+ F	3-27-79	92	42.5	A	DL WQ	
4CDB1	3,026	610	10	51	X	---	3-15-79	3,000 E	34.0	S	DL WQ	
4CDC1	3,022	750	12	116	X	89+	8-20-79	1,540	35.0	S	DL	
4CDD1	3,010	755	6	518	X	---	8-16-79	1,130	33.0	S	DL	
4DCC1	2,920	590	8	550	X	166+ F	12- 8-78	100	35.0	A	DL WQ	
6CDA1	3,400	---	4	---	--	109.60	4- 6-79	---	---	H		
9ADA1	2,930	750	6	332	X	362+ F	3-14-79	164	33.0	A	DL WQ	
9ADB1	2,980	530	6	495	X	102+ F	3-14-79	200	32.0	A	DL WQ	
9ADC1	3,000	850	6	380	X	167+	3-15-79	65	31.5	A	DL WQ	
9BAA1	3,060	578	12	45	X	---	4- 5-79	477	32.0	S	DL	
10CBB1	2,950	615	6	488	X	93+ F	3-14-79	70	32.5	A	DL WQ	
13DDD1	3,514	900	6	425	X	4+	3-27-79	7	26.0	I	DL WQ	
14BDD1	3,205	---	6	---	--	56.09	4- 6-79	---	---	H		
17BAA1	3,360	415	6	214.5	X	153.68	2-22-79	---	---	H	DL	
21ADD1	3,347	80	6	---	--	61.45	4- 5-79	---	---	H		
23ABD1	3,345	350	6	39	X	29+	3-27-79	30	25.0	H	DL WQ	

Table 1. Records of wells—Continued

Well number	Altitude of land surface (feet above National Geodetic Vertical Datum of 1929)	Reported depth of well (feet below land surface)	Casing		Water level			Discharge (gal/min) flowing, unless otherwise indicated	Temperature of water (°C)	Use of water	Remarks
			Diameter (in)	Feet below land surface to first perforation	Well finish	Feet above (+) or below land surface	Date measured				
36DAC1	3,782	904	16	686	X	96 R	----	260	29.0	P	WQ
10S-12E-2CBA1	3,735	---	--	---	--	365.70	2-21-79	---	---	I	
12CDC1	3,742	500	20	10	X	366.48	2-21-79	---	24.5 R	I	DL
10S-13E-5CCA1	3,823	575	12	100	X	448.88	3- 6-79	---	---	I	DL
14DAC1	3,900	---	12	---	--	258.94	2-21-79	---	---	I	
25CDC1	3,860	250	6	---	--	68.73	3- 7-79	---	---	H	
10S-14E-1CAA1	3,840	688	--	---	--	58.22	2-21-79	---	---	I	
5CBB1	3,665	176	--	---	--	26.43	2-21-79	---	---	I	
21DCC1	3,850	---	--	---	--	47.97	2-23-79	---	---	I	

10°C give a thermal gradient of 1.35°C/100 ft. To attain a temperature of 70°C for this gradient, water must circulate to a depth of about 4,400 ft. In the Banbury area, water temperatures near 70°C occur in wells 420 to 700 ft deep, which suggests there is considerable convective fluid transfer, probably upward along faults, to achieve 70°C temperatures at depths shallower than 4,400 ft.

Fluctuations in Discharge and Artesian Head

As part of this study, two thermal wells were selected in which to continuously monitor fluctuations in discharge and artesian head. Well 9S-14E-4CDB1, which supplies water for catfish production, was equipped to monitor discharge, and well 9S-14E-4BBD1, which is unused, was equipped to monitor pressure fluctuations. Locations of these two wells are shown in figure 3. The discharge hydrograph for well 9S-14E-4CDB1 is shown in figure 4, and the water-level hydrograph for well 9S-14E-4BBD1 is shown in figure 5.

As shown by figures 4 and 5, the records are not long enough to complete one annual cycle of fluctuation; therefore, little interpretation of the records can be made. The flow rate for well 9S-14E-4CDB1 (fig. 4) declined from 3,110 gal/min in April 1979 to 1,550 gal/min in March 1980. The calculated head in well 9S-14E-4BBD1 (fig. 5) declined from 164 ft above land surface in July 1979 to 146 ft above land surface in March 1980. These declines may reflect seasonal fluctuations or may indicate a decrease in reservoir pressure due to development of the resource. Continued monitoring may provide more data for determining the cause of the decline.

WATER CHEMISTRY

Chemical Character

Samples of thermal water (water temperature greater than 20°C) were collected from 21 wells and 2 springs in and near the Banbury Hot Springs area. Temperatures of the water range from 25° to 72°C. Results of the chemical analyses, including common ions, silica, and the minor elements—arsenic, boron, lithium, and mercury—for the samples collected, are listed in table 2. Well and spring locations are shown in figure 3.

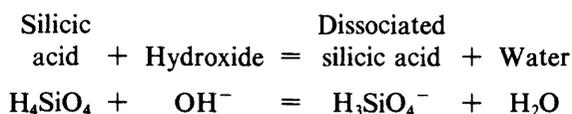
The thermal ground waters sampled are a sodium carbonate or bicarbonate type and are slightly alkaline (pH, 7.9-9.5). Concentrations of dissolved solids generally increase with water temperature and range from 231 mg/L in water at 31.5°C to 422 mg/L in water at 72.0°C. Concentrations of chloride, fluoride, and boron also increase from the lower temperature water to the higher temperature water.

Chemical Geothermometers

Reservoir temperatures in the Banbury Hot Springs area were estimated by using the silica geothermometer (Fournier and Rowe, 1966) and the Na-K-Ca geothermometer (Fournier and Truesdell, 1973). Temperatures estimated by these chemical geothermometers are valid only for hot-water systems and only if the following basic assumptions are met (Fournier, White, and Truesdell, 1974): (1) the chemical reactions at depth are temperature dependent, (2) an adequate supply of chemical constituents used for the thermometry is present in the

reservoir, (3) chemical equilibrium is established at depth between the hot water and the reservoir minerals, (4) there is negligible reequilibration of the chemical composition of the hot water as it rises to the surface, and (5) hot water rises rapidly to the surface with no dilution or mixing of hot and cold water.

Dissolved silica (SiO_2) reported in chemical analyses is actually present as silicic acid (H_4SiO_4) and various dissociated species (particularly H_3SiO_4^-); SiO_2 does not exist as a distinct dissolved species in nature (Brook and others, 1979). In alkaline water, hydroxide (OH^-) reacts with the silicic acid to reduce the proportion of silicic acid to total dissolved silica in the temperature-dependent reaction:



Thermal waters in the study and adjacent areas are slightly alkaline (pH values, 7.9–9.5; table 2). For water that has a pH greater than about 8.3, reported values for dissolved silica ($\text{H}_4\text{SiO}_4 + \text{H}_3\text{SiO}_4^-$) were reduced by the concentration of H_3SiO_4^- calculated for the pH of the water. Corrected values for dissolved silica were used in the silica geothermometers that assume equilibrium with both quartz and chalcedony.

No magnesium correction was applied when using the Na-K-Ca geothermometer. In most of the thermal water sampled, concentration of magnesium was less than 1 mg/L and any correction would be minimal. Analysis of water from one well indicated a magnesium concentration of 3.9 mg/L; however, a reservoir temperature of 74°C that was estimated when using the Na-K-Ca geothermometer is very close to the limiting temperature of 70°C suggested by Fournier and Potter (1979), and no correction was made. Analyses of water from two other wells indicated magnesium concentrations greater than 1 mg/L, but these wells are about 5 mi southeast of the other thermal wells, and no corrections were applied.

Estimated reservoir temperatures and departure from theoretical equilibrium (degree of saturation or unsaturation) for aragonite, calcite, chalcedony, and quartz were calculated for the thermal waters (table 3), using a computer program modified from the SOLMNEQ program of Kharaka and Barnes (1973). Relative departure from theoretical equilibrium for the four minerals is considered in selecting the geothermometer to determine the best estimate of reservoir temperature. R. H. Mariner (oral commun., 1979) suggested that chalcedony may control the silica solubility in thermal water having a temperature below about 75°C at the surface. This seems to be true for most of the cooler unmixed thermal water; however, 57° to 72°C water from several wells and one spring in the vicinity of Salmon Falls Creek is unsaturated with chalcedony, and quartz probably controls the silica solubility.

Fournier, Sorey, Mariner, and Truesdell (1979) showed that, on a plot of reservoir temperatures estimated by the silica geothermometer versus reservoir temperatures estimated by the Na-K-Ca geothermometer, most unmixed water in equilibrium plots on or near an equal-temperature line having a slope of 1. Water that plots significantly above the equal-temperature line probably has undergone evaporation or has dissolved amorphous silica from the reservoir material. Water that plots significantly below the equal-temperature line probably has mixed with another type of water and has not reequilibrated, precipitated silica during cooling, or precipitated calcite or aragonite due to loss of CO_2 (Fournier, Sorey, Mariner, and Truesdell, 1979).

A comparison of reservoir temperatures estimated by the H_3SiO_4^- -corrected silica and Na-K-Ca geothermometers is shown in figure 6. With the exception of water from wells and springs in the vicinity of Salmon Falls Creek, chalcedony is assumed to control the silica solubility. Water that plots on or near the equal-temperature line is probably unmixed. This includes the 57° to 72°C water from wells and springs in the vicinity of Salmon Falls Creek and 31.5° to 33.0°C water from wells near Deep Creek. These waters are considered to comprise the unmixed components from which most of the other thermal waters in the study area are derived. Other waters, with temperatures between about 30° and 60°C, plot below the equal-temperature line in figure 6 and, lacking any evidence to indicate precipitation of silica, calcite, or aragonite, are probably mixed waters that have not equilibrated. Some waters plot significantly above the equal-temperature line. These waters probably contain amorphous silica dissolved from the reservoir materials but were sampled from wells 3 to 8 mi southeast of the study area and are not included in a discussion of the Banbury thermal water.

Samples of thermal water were collected from two wells and one spring for sulfate-water isotope analyses. For water containing even small amounts of H_2S , analyses for $^{18}\text{O}(\text{SO}_4)$ may be affected by the formation of additional sulfate due to oxidation of H_2S to H_2SO_4 by sulfur-oxidizing bacteria. Possible effects due to oxidation were minimized by adding 5 mL (milliliter) of formaldehyde to each sample to kill any bacteria and to preclude the formation of H_2SiO_4 by oxidation of H_2S . Estimated reservoir temperatures, using the sulfate-water geothermometer and assuming conductive cooling for samples 3, 5, and 7 (table 3), were 90°, 93°, and 101°C, respectively. On the basis of significant differences in temperature and concentrations of chloride and dissolved solids, thermal water represented by samples 5 and 7 is probably mixed water, and the 90°C obtained for sample 3 is probably the best estimate of the thermal reservoir temperature obtained by using the sulfate-water geothermometer.

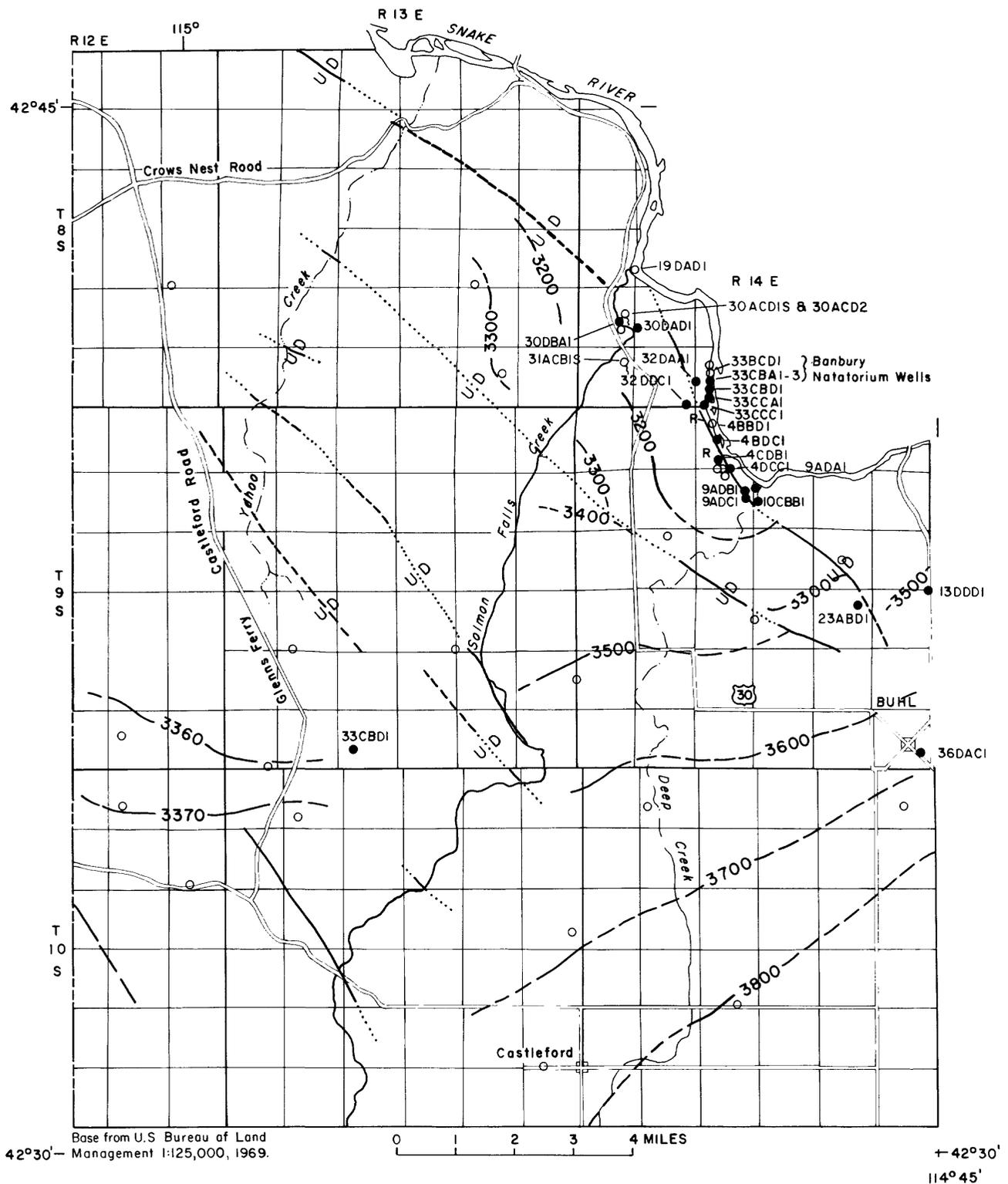


Figure 3. Potentiometric-surface contours and

Based on the $H_3SiO_4^-$ -corrected chalcedony and Na-K-Ca geothermometers, reservoir temperatures near Deep Creek are about $71^\circ C \pm 4^\circ$. Based on the

10 Geothermal Resources, Banbury Hot Springs Area, Idaho

$H_3SiO_4^-$ -corrected quartz, Na-K-Ca, and sulfate-water geothermometers, reservoir temperatures in the vicinity of Salmon Falls Creek are about $94^\circ C \pm 4^\circ$.

EXPLANATION

- 3300 — Potentiometric-surface contour, spring 1979, dashed where approximately located. Contour interval is variable. Datum is National Geodetic Vertical Datum of 1929
- o Well
- ^Ro Well equipped with recorder
- Well and number for which water-quality analysis is given (table 2)
32DAAI
- ^Q30ACDIS Spring and number for which water-quality analysis is given (table 2)
- · · · Fault—Dashed where approximately located; dotted where concealed. U, upthrown side; D, downthrown side (Malde, Powers, and Marshall, 1963; and Malde and Powers, 1972)

well and spring locations, Banbury Hot Springs.

Isotopes

Samples of thermal water from selected wells and springs were collected for analysis of tritium, oxygen-18,

and deuterium. Isotopic compositions of thermal fluids can be used to indicate age, origin, and mixing patterns in the geothermal system.

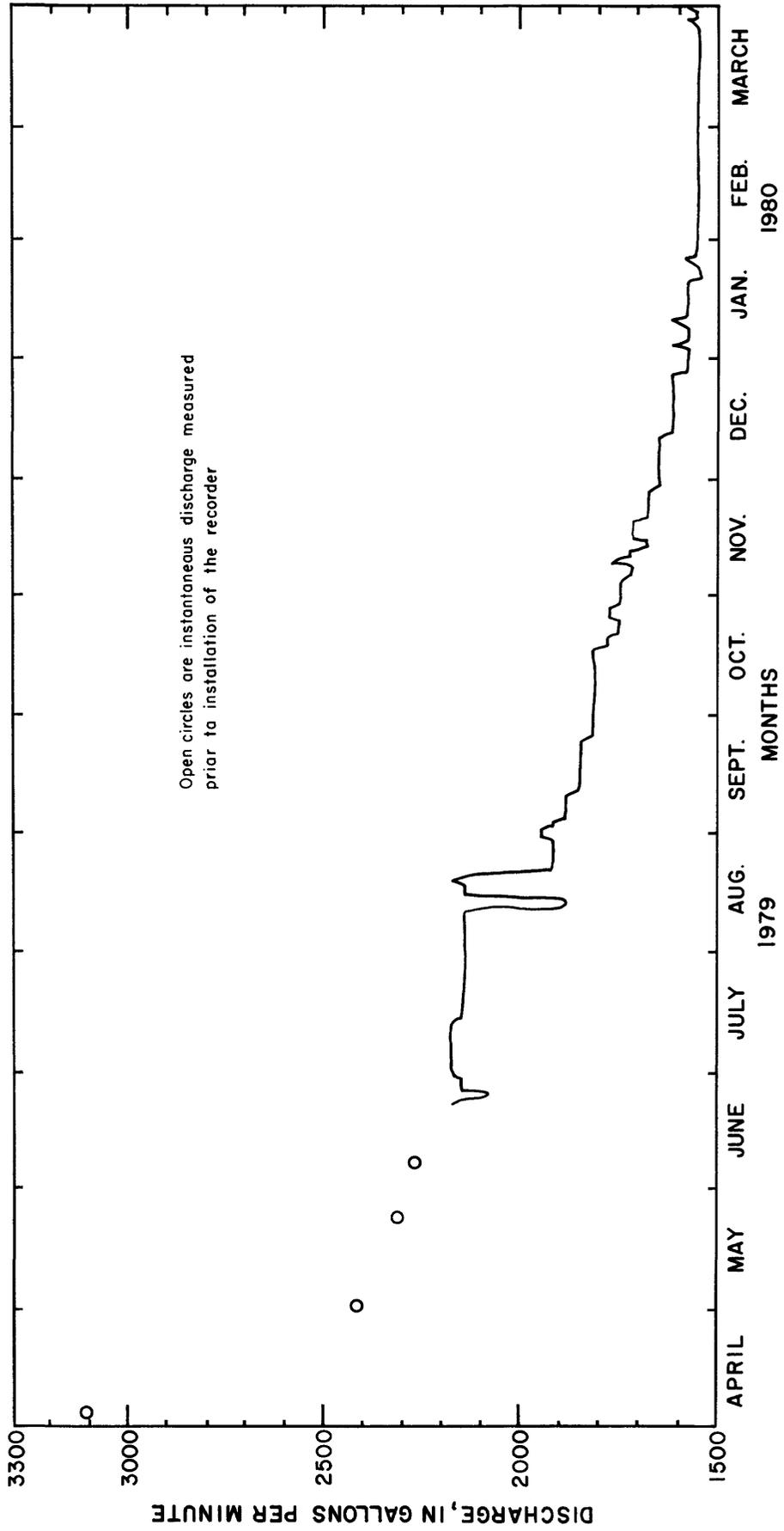


Figure 4. Discharge from well 9S-14E-4CDB1.

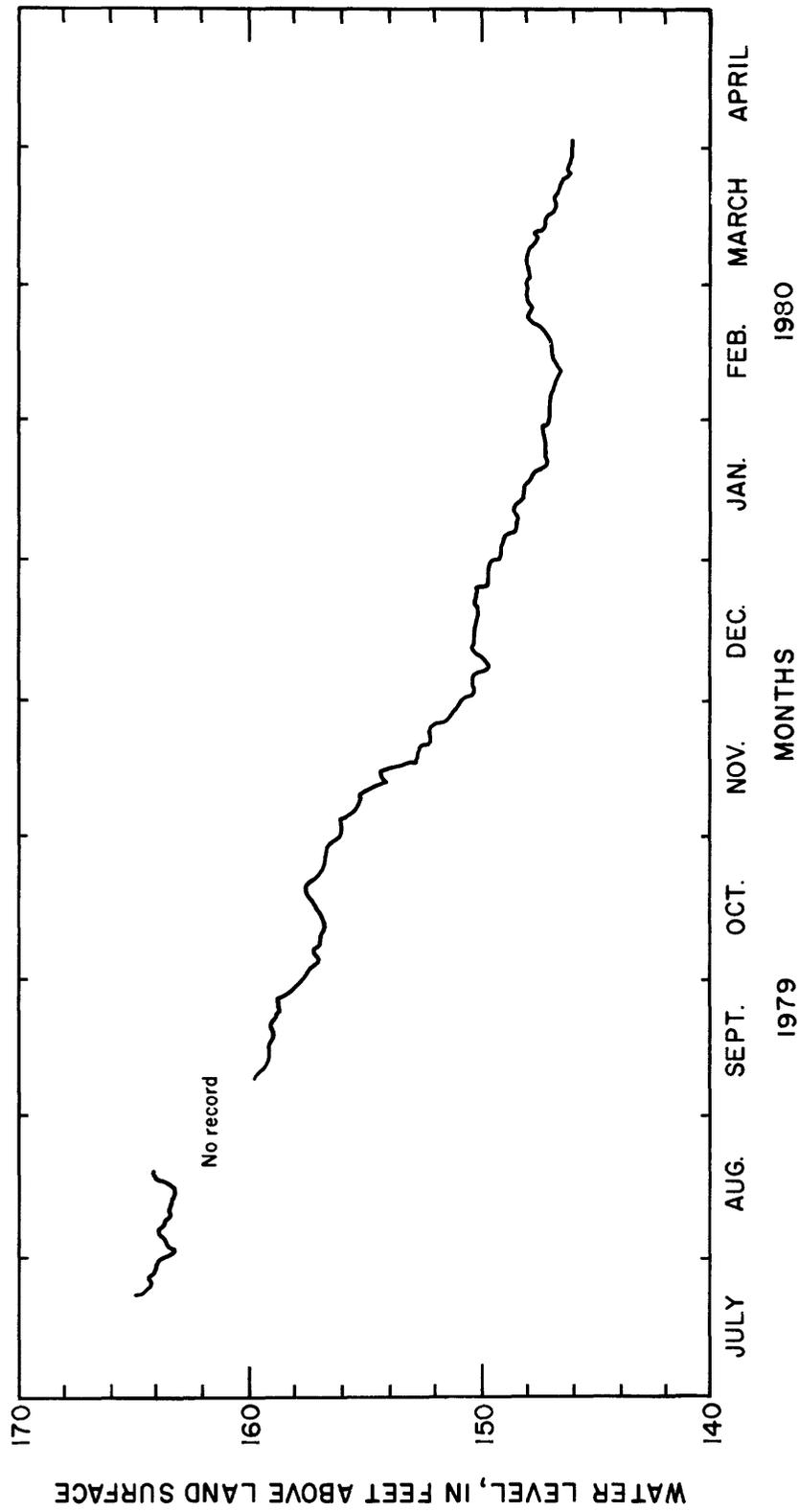


Figure 5. Water levels in well 95-14E-4BBD1.

Table 2. Chemical analyses of water
[Chemical constituents in milligrams per liter, except

Spring or well number	Reported well depth below land surface (ft)	Date of collection	Flow rate (gal/min)	Specific conductance (μ mhos)	pH	Water temperature ($^{\circ}$ C)	Hardness as CaCO ₃	Noncarbonate hardness	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Percent sodium
8S-14E-30ACD1S	---	2- 8-78	40	601	9.1	70.5	3	0	1.2	<.1	140	99
30ACD2	420	8-15-79	120	633	9.3	72.0	3	0	.9	.1	140	99
30DAD1	700	3-26-79	9	634	9.4	62.0	2	0	.7	<.1	150	99
30DBA1	450	4-25-79	650	646	9.5	71.5	4	0	1.5	.1	140	98
31ACBIS	---	4- 5-79	290	566	9.4	57.0	2	0	.9	<.1	130	99
32DAA1	545	8-15-79	10	449	9.1	45.5	3	0	.9	.1	100	98
32DDC1	553	4- 4-79	170	394	9.3	42.5	4	0	1.3	.1	90	97
33CBA1	110	2- 8-78	60	454	9.0	59.0	3	0	1.1	<.1	100	98
33CBA2	342	4- 4-79	---	466	9.3	59.0	3	0	1.1	<.1	110	98
33CBD1	540	3-15-79	4	459	9.2	42.0	10	0	3.7	.2	100	94
33CCA1	510	3-15-79	80	441	9.4	44.5	8	0	3.3	<.1	100	95
33CCC1	480	3-26-79	12	434	9.3	30.0	2	0	.9	<.1	97	98
9S-13E-33CBD1	840	6-26-78	1,200	326	8.0	30.0	81	0	26	3.9	35	46
9S-14E-4BDC1	375	3-27-79	92	426	9.2	42.5	4	0	1.3	.1	93	97
4CDB1	610	3-15-79	3,000	322	8.7	34.0	14	0	5.4	.2	66	89
4DCC1	590	12- 8-78	100	305	8.3	35.0	21	0	7.8	.3	63	84
9ADA1	750	3-14-79	164	326	8.4	33.0	30	0	11	.5	61	79
9ADB1	530	3-14-79	200	311	8.4	32.0	21	0	8.0	.2	62	85
9ADC1	850	3-15-79	65	307	8.6	31.5	20	0	7.5	.3	63	85
10CBB1	615	3-14-79	70	316	8.3	32.5	27	0	10	.5	62	81
13DDD1	900	3-27-79	7	321	8.3	26.0	19	0	7.4	.2	62	84
23ABD1	350	3-27-79	30	330	8.1	25.0	47	0	17	1.1	53	67
36DAC1	904	3-14-79	260	499	7.9	29.0	110	0	36	5.4	61	52

¹ Total alkalinity distributed as carbonate and bicarbonate at the spring water temperature and pH.

Tritium

Tritium (³H), a radioactive isotope of hydrogen, is formed in the upper atmosphere during bombardment by subatomic particles from outer space. It decays with a half-life of about 12.4 years and is introduced into the water cycle in rain and snow. Although concentrations of tritium in precipitation vary both seasonally and geographically, prior to extensive thermonuclear testing between 1954 and 1963, tritium levels in precipitation were generally less than about 10 but were as high as about 20 TU (tritium units; one TU equals ³H/H of about 10). By 1963, worldwide tritium levels in precipitation had increased dramatically and were reported to be 7,000 TU in

the vicinity of Yellowstone National Park (Pearson and Truesdell, 1978). Since the completion of atmospheric nuclear tests, tritium levels in precipitation have declined and in 1977 averaged about 50 TU.

Tritium in a ground-water system is a function of tritium concentration in the recharge water and the residence time and nature of flow in the system. The following basic types of flow models are discussed in detail by Nir (1964): (1) the piston-flow model, which has parallel flow lines of constant and equal velocity, so that a water sample taken at some point would include only water originating at the point of recharge, and (2) the completely mixed reservoir model, where it is assumed that the recharge water is continually and instantly mixing throughout the entire

from selected wells and springs
 where noted. ---, no data available; <, less than]

Sodium-adsorption ratio (SAR)	Potassium (K)	Bicarbonate ¹ (NCO ₃)	Carbonate ¹ (CO ₃)	Alkalinity as CaCO ₃	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Silica (SiO ₂)	Dissolved solids (calculated)	Nitrite plus nitrate as N (NO ₂ + NO ₃)	Phosphorus, total as P	Arsenic (As), µg/L	Boron (B), µg/L	Lithium (Li), µg/L	Mercury (Hg), µg/L
35	1.1	70	45	132	32	50	27	89	420	0.06	0.01	60	440	60	<0.1
37	1.2	59	52	135	35	51	27	86	422	.01	<.01	52	470	60	.1
49	1.4	56	55	138	35	48	15	84	417	.01	<.01	43	490	50	<.1
30	1.5	56	55	138	33	51	27	82	419	<.01	.01	42	510	60	.2
38	1.5	59	58	145	34	34	21	86	394	<.01	.01	48	340	40	.1
27	1.8	100	31	134	29	30	26	86	354	<.01	.01	29	230	40	<.1
20	1.7	85	31	121	28	14	9.4	67	284	.01	.01	28	170	40	.2
26	1.5	90	35	132	27	25	14	100	348	.03	.01	40	230	40	<.1
29	1.6	78	46	141	30	23	15	88	353	<.01	.02	36	260	40	.1
14	2.1	88	38	135	27	23	13	94	344	.02	.01	32	230	30	<.1
15	1.8	83	38	131	27	22	12	88	333	.02	.01	29	230	40	<.1
28	1.6	85	34	126	28	20	13	64	300	<.01	.01	27	210	30	.1
1.7	7.9	120	0	98	35	16	1.8	86	270	1.0	<.01	9	60	50	<.1
21	1.7	89	34	130	27	24	12	76	313	<.01	<.01	31	210	30	.1
7.6	2.9	110	7	102	30	13	3.7	56	238	.01	<.01	22	120	50	<.1
6.0	4.0	140	0	115	22	13	3.6	54	237	.01	<.01	18	100	60	<.1
4.9	3.9	150	4	130	24	11	3.1	53	246	<.01	<.01	16	110	60	<.1
5.9	2.8	140	2	118	26	11	3.1	53	237	<.01	<.01	21	110	50	<.1
6.1	2.8	120	7	110	26	11	3.2	51	231	.01	<.01	23	120	50	<.1
5.2	3.5	150	0	123	25	11	2.9	51	240	<.01	<.01	19	110	50	<.1
6.1	5.6	140	0	110	21	9.9	4.8	82	259	.34	<.01	8	140	80	<.1
3.4	7.5	160	0	130	22	14	2.4	87	282	.61	2.8	8	120	50	<.1
2.5	10	170	0	139	61	31	1.9	66	356	1.5	<.01	9	120	70	.2

system. The tritium concentration in water of various residence times, assuming piston flow and mixed reservoir systems, in Yellowstone National Park was calculated by Pearson and Truesdell (1978) and is shown in figure 7. Curves similar to those in figure 7 probably would result for thermal ground-water systems in south-central Idaho.

Water samples for tritium analyses were obtained from four thermal wells in the study area and one thermal spring about 60 mi south but still within the Salmon Falls Creek drainage area. Samples were predistilled and enriched by electrolysis; enriched aliquots of 470-mL samples were counted by a gas proportional counter. Results of tritium analyses of thermal water samples are shown in table 4; errors are given for one standard deviation and

include those incurred during radioactive counting, as well as volume errors. For the 470-mL enrichment method, the minimum error is 0.1 to 0.2 TU. All samples were corrected for tritium decay to the collection date, using a half-life of 12.350 years. Concentrations of tritium in the thermal water sampled ranged from 0 ± 0.1 to 4.1 ± 0.2 TU.

If the thermal water moves by piston flow, the tritium level (T) in a water sample taken at any point within the system will be related to the tritium concentration in the water during recharge (T₀) and the transit time or age (t) of the sample by,

$$T = T_0 e^{-\gamma t},$$

where the decay constant $\gamma = \ln 2/\text{half-life of tritium}$. If

Table 3. Estimated reservoir temperatures and free energy of formation for selected thermal wells and springs
[--, values not computed for pH 8.3 or less]

Well or spring number	Estimated reservoir temperatures based on geothermometers						Free energy of formation ¹				Reference No. (fig. 6)
	Water temperature at the surface (°C)	Silica quartz conductive (°C)	Silica quartz conductive H ₃ SiO ₄ ⁻ corrected (°C)	Sodium-potassium-calcium (°C)	Silica chalcedony (°C)	Silica chalcedony H ₃ SiO ₄ ⁻ corrected (°C)	Aragonite	Calcite	Chalcedony	Quartz	
8S-14E-30ACD1S	70.5	131	96	92	103	66	0.2	0.3	-0.1	0.4	1
30ACD2	72.0	129	90	93	101	81	.1	.2	-.3	.2	2
30DAD1	62.0	128	93	98	100	48	-.1	.0	-.2	.3	3
30DBA1	71.5	126	68	98	99	36	.5	.6	-.5	.1	4
31ACB1S	57.0	129	99	103	101	52	.1	.1	-.1	.4	5
32DAA1	45.5	129	105	116	101	75	-.3	-.2	.4	.9	6
32DDC1	42.5	116	86	100	87	55	.0	.1	.2	.7	7
33CBA1	59.0	137	111	108	110	81	-.1	.0	.3	.8	8
33CBA2	59.0	130	89	108	103	58	.1	.2	.0	.5	9
33CBD1	42.0	134	106	84	107	77	.6	.7	.5	1.0	10
33CCA1	44.5	130	96	82	103	66	.6	.7	.3	.8	11
33CCC1	30.0	114	91	112	85	61	-.3	-.3	.4	1.0	12
9S-13E-33CBD1	30.0	129	--	74	101	--	.0	.0	.9	1.5	13
9S-14E-4BDC1	42.5	122	96	101	94	66	.0	.0	.3	.9	14
4CDB1	34.0	107	100	82	78	70	.1	.1	.5	1.1	15
4DCC1	35.0	105	--	85	76	--	-.2	-.1	.5	1.1	16
9ADA1	33.0	104	101	75	75	71	.2	.3	.5	1.1	17
9ADB1	32.0	104	101	72	75	71	-.1	.0	.5	1.1	18
9ADC1	31.5	103	97	73	73	67	.1	.2	.5	1.1	19
10CBB1	32.5	103	--	74	73	--	.0	.1	.5	1.1	20
13DDD1	26.0	126	--	97	97	--	-.3	-.3	.9	1.5	21
23ABD1	25.0	130	--	86	102	--	-.1	.0	1.0	1.5	22
36DAC1	29.0	115	--	80	86	--	.2	.2	.7	1.3	23

¹ Values are departure from theoretical equilibrium in kilocalories; (+) values indicate supersaturation, (-) values indicate unsaturation. Calculations from computer program SOLMNEQ (Kharaka and Barnes, 1973).

the Banbury thermal waters are part of a piston-flow system, assuming an upper limit of 20 TU, samples that overlap 0 TU could indicate a residence time near 100 years and virtually no mixing with younger water. If these waters are part of a well-mixed system, residence times could exceed 1,000 years.

Constraints applied by the hydrologic model developed for the Banbury geothermal system (discussed more fully in a later section) require some local mixing of water of at least two slightly different compositions. Consequently, thermal water having a concentration of tritium ≤ 0.1 TU is interpreted as being at least 100 years old and perhaps more than 1,000 years old. This water mixes with varying amounts of younger water to give local differences in temperature and isotopic and chemical composition. In table 4, a sample from well 9S-14E-9ADA1 has a tritium concentration of 4.1 ± 0.2 TU and is probably mixed water. A concentration of about 4 TU would result in a

piston-flow system for water having a residence time of about 29 years and no mixing with post-1954 water or could have resulted from a mixture of 90 percent older zero-tritium water and 10 percent young local water. Further discussion of mixing is included in the next section.

Table 4. Concentrations of tritium in water sampled from selected thermal wells and springs

[Tritium analysis by T. A. Wyerman, U.S. Geological Survey, Reston, Va.]

Well or spring number	Temperature (°C)	Tritium (TU)
85-14E-30DAD1	62.0	0.1 \pm 0.1
8S-14E-32DDC1	42.5	0.2 \pm 0.1
9S-14E-9ADA1	33.0	4.1 \pm 0.2
9S-14E-36DAC1	29.0	0 \pm 0.1
46N-64E-23BBD1S	24.0	0 \pm 0.1

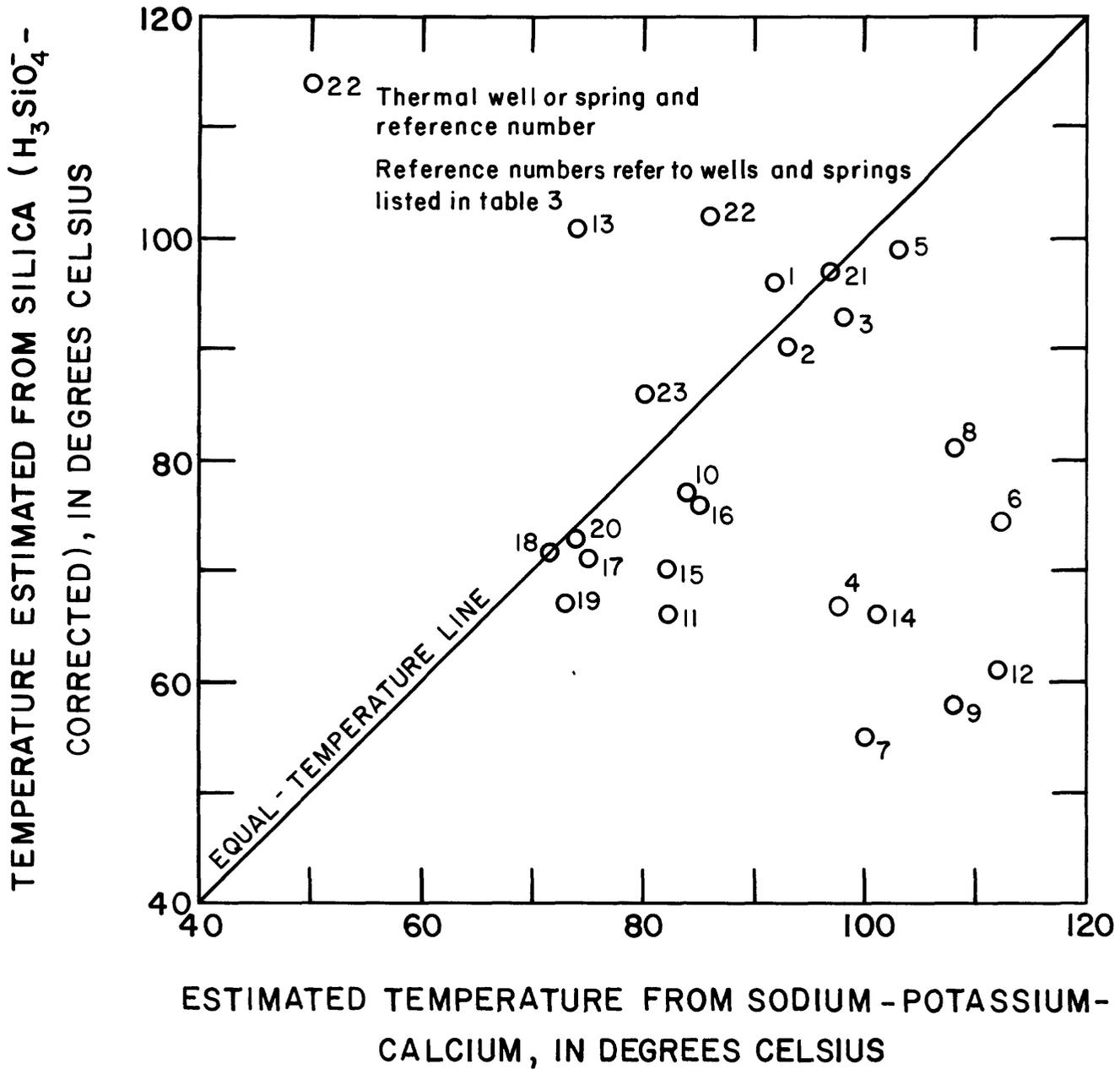


Figure 6. Comparison of reservoir temperatures estimated by the silica and sodium-potassium-calcium geothermometers.

Deuterium and Oxygen-18

Concentration of the stable isotopes, deuterium (D) and oxygen-18 (^{18}O), in water from different sources characterizes and indicates the origin and mixing pattern of individual water.

Principal stable molecular species in water are $H_2^{16}O$, $H_2^{17}O$, $H_2^{18}O$, and $HD^{16}O$. In seawater, the proportions of these species are 10⁶:2,000:420:316 (Craig, 1963); this composition is referred to as SMOW (standard mean ocean water). Precipitation, which is derived from ocean water, is depleted in the stable isotopes due to evaporation. Stable-isotope concentrations are generally

expressed in delta units (δ) and are reported in parts per mil (‰) or parts per thousand. These units represent relative deviations in the heavy isotope fraction in water and are defined as

$$\delta = \left[\frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \right] \times 1,000,$$

where

- R_{sample} = ratio or isotopic concentration ($^{18}O/^{16}O$, D/H) of the sample, and
 R_{standard} = ratio of isotopic concentration of the standard SMOW.

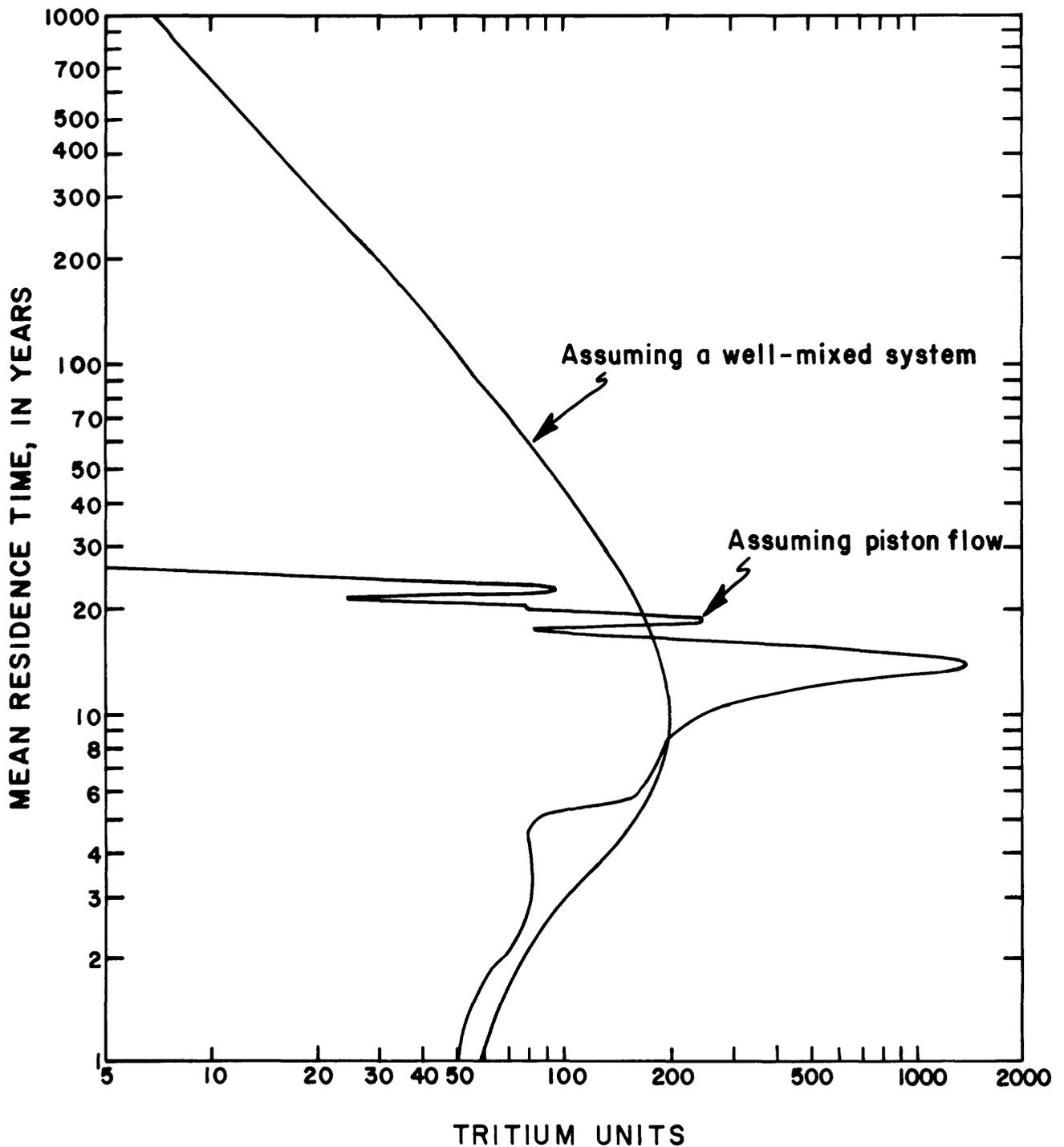


Figure 7. Relation of tritium concentration to residence time, assuming piston-flow and well-mixed ground-water systems in Yellowstone National Park.

A worldwide study of freshwater samples by Craig (1963) showed that the isotopic reactions in cold meteoric water could be expressed by the equation $\delta D = 8\delta^{18}O + 10$. A plot of this equation is a straight line, commonly referred to as the SMOW line, and is shown in figure 8. Surface water affected by extensive nonequilibrium evap-

oration, as in inland basins, lie off this line. However, at ordinary air temperatures, evaporated surface water is connected approximately to the original precipitation composition $\delta^{18}O_0, \delta D_0$, by a line expressing the equation, $\delta D = 5(\delta^{18}O - \delta^{18}O_0) + \delta D_0$ (Ellis and Mahon, 1977).

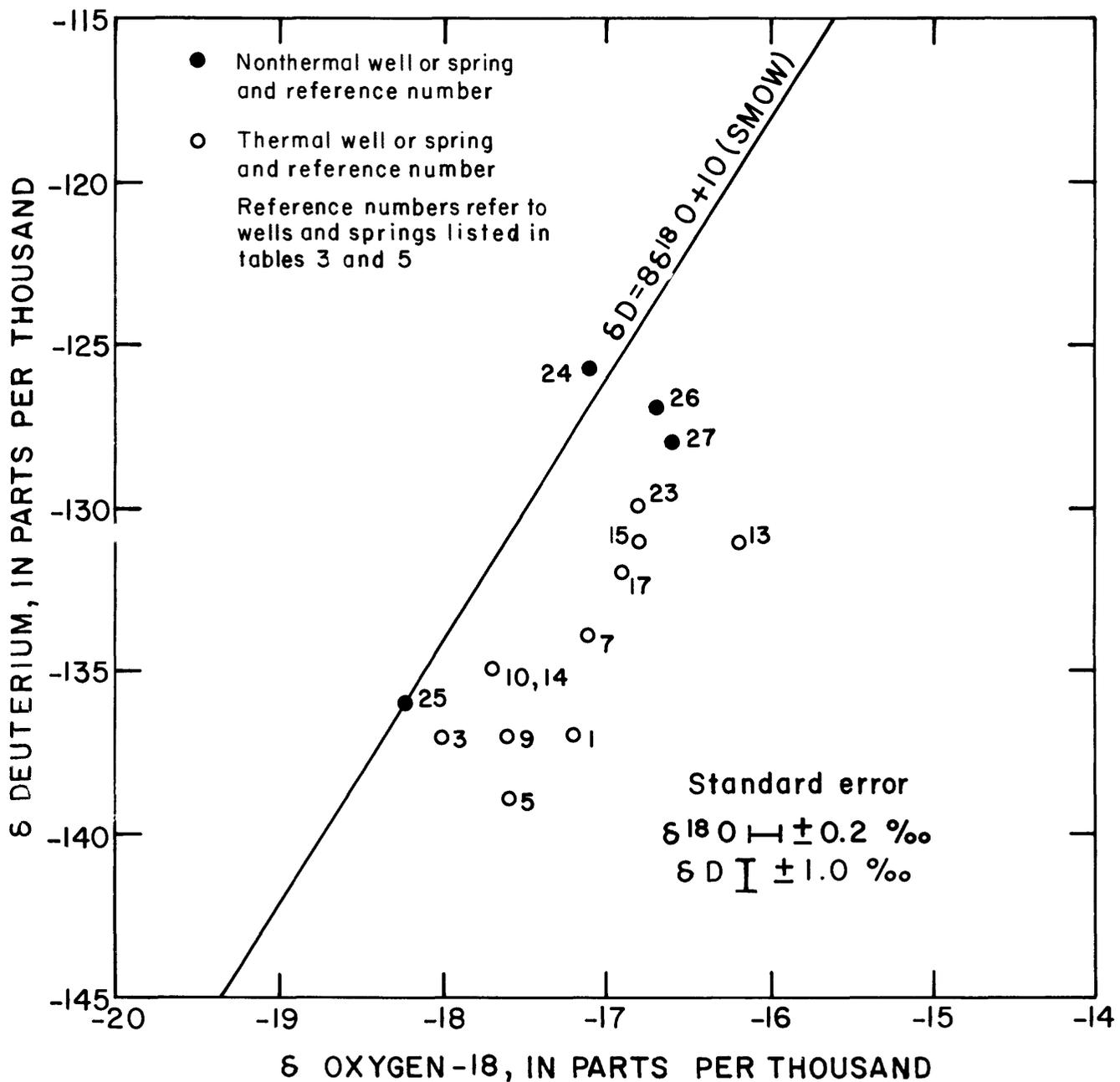


Figure 8. Relation between concentrations of deuterium and oxygen-18.

During passage through the reservoir, thermal water and nonthermal water retain the deuterium composition characteristic of precipitation in the recharge area. The ^{18}O content in thermal water, however, is usually enriched (becomes less negative) to varying degrees during circulation within the system due to reaction with the more enriched ^{18}O of the reservoir material. For a more complete discussion of stable-isotope geochemistry, refer to Gat (1971) or Ellis and Mahon (1977).

Samples of thermal water were collected for analyses of ^{18}O and deuterium from nine wells and two springs in and near the study area. Due to the reconnaissance nature and

limited extent of this investigation, no cold-water samples from potential recharge areas were collected. For discussion, results of existing stable-isotope analyses for several nearby cold-water springs are included in table 5 and figure 8.

Figure 8 is a graph showing the stable-isotope data in standard δ values (‰) relative to SMOW. The wide range of deuterium in the samples between about -139‰ and -130‰ indicates mixing of water from at least two sources. If only one source of recharge were involved, the deuterium values for all the thermal waters would be more nearly identical because there is no

mechanism for deuterium exchange during deep circulation through the system (A. H. Truesdell, written commun., 1975).

Thermal waters having the hottest temperatures measured at the surface occur in wells in the vicinity of Salmon Falls Creek and are represented by point 1 in figure 8. These waters, having surface temperatures near 72°C, seem to be unmixed and are probably representative of the deep circulating hot water in the Banbury system. The recharge area for the unmixed hot water is unknown.

Cold meteoric water isotopically similar to 25 in figure 8 could, by long contact at temperatures near 100°C, become enriched in ¹⁸O to yield water similar to 1. Although cold water represented by 25 presently occurs in the mountains 60 mi southeast of the Banbury area, isotopically similar water might occur as recharge in the higher altitudes nearby to the southeast. Additional stable-isotope analyses of the cold water from that area are necessary to confirm this, however.

Cold water, represented by 24, 26, and 27 (fig. 8), was sampled from springs southwest of the study area in the Jarbidge Mountains. On the basis of tritium analyses, these cold waters are probably less than 20 years old. Samples 26 and 27 may have undergone some evaporation before percolating to the saturated zone but, in general, are probably representative of recent recharge water for areas to the southwest (Young and Lewis, 1980). Meteoric water that recharges the shallow ground-water system in the Banbury area would be similar but somewhat more depleted isotopically relative to SMOW.

Although not as enriched in ¹⁸O, thermal water represented by 3 and 9 (fig. 8) is similar in deuterium to the

hottest water, 1, and probably originated as precipitation in about the same general vicinity. Lack of any significant enrichment in ¹⁸O for water 3 may be due to shorter residence time or shallower depth of circulation of the water. Water similar to 10 and 14 could result from mixing of either 1, 3, or 9 with cooler local ground water.

Water represented by 5 (fig. 8) is from a thermal spring in Salmon Falls Creek Canyon about 2 mi from the main Banbury area and about 1 mi from the wells that produce the hottest water. The depletion in deuterium relative to the hottest water indicates that this water was recharged in a different area.

Thermal water represented by 7, 15, 17, and 23 (fig. 8) could result from mixing of hot water, similar to 1, with cooler local ground water, which more nearly resembles, isotopically, the cold water represented by 24, 26, and 27. Water represented by 23 is from a municipal well and may reflect some mixing with shallow ground water affected by local irrigation or urbanization. Water represented by 13 is from a well about 8 mi southwest from the Banbury Hot Springs area and is isolated, hydrologically, by numerous faults. Chemically and isotopically, this water is similar to some of the thermal water in southwestern Idaho described by Young and Lewis (1980) and to the thermal waters southeast of the Banbury area that were sampled during this study. The large oxygen shift evident for sample 13 may be due, in part, to evaporation prior to being recharged to the regional thermal ground-water system.

Further indication of mixing of water of different compositions and temperatures to give the physical and chemical variations evident in Banbury thermal waters is shown by the comparisons in figures 9–12. Figure 9 shows

Table 5. Stable-isotope analyses of water sampled from selected wells and springs

Well or spring number	t°C	δ ^D SMOW	δ ¹⁸ O SMOW	Δ ¹⁸ O(OH)	Reference symbol (fig. 8)
85-14E-30ACD1S	70.5	-137	-17.2	+1.17	1
30DAD1	62.0	-137	-18.0	+ .38	3
31ACB1S	57.0	-139	-17.6	+1.02	5
32DDC1	42.5	-134	-17.1	+ .90	7
33CBA2	59.0	-137	-17.6	+ .63	9
33CBD1	42.0	-135	-17.7	+ .42	10
9S-13E-33CBD1	30.0	-131	-16.2	+1.37	13
9S-14E-4BDC1	42.5	-135	-17.7	+ .42	14
4CDB1	34.0	-131	-16.8	+ .77	15
9ADA1	33.0	-132	-16.9	+ .85	17
36DAC1	29.0	-130	-16.8	+ .70	23
¹ 14S-14E-11CAB1S	12.0	-126	-17.1	- .01	24
² 15S-23E-14DDC1S	5.0	-136	-18.2	0	25
¹ 46N-60E-13ACC1S	4.0	-127	-16.7	+ .43	26
¹ 45N-55E-25DAA1S	6.5	-128	-16.6	+ .65	27

¹ Young and Lewis (1980)

² Unpublished data from A. H. Truesdell

the relation between chloride and deuterium for water in the Banbury area. Cold water similar to water represented by 25 in figure 9, and subject to constraints imposed by temperature and residence time, could result in thermal water having a chloride concentration that plots anywhere along an extension of line 1-9. Thermal water thus formed could mix with cold water similar in composition to 26 to produce any chemical variation of thermal water that would plot on a line radial to 26 between 26 and line 1-9. Similar relations of chloride with enthalpy, oxygen-18, and fluoride for thermal water of the Banbury area are apparent in figures 10-12.

In figures 9-12, water represented by point 23 is ignored due to probable influence on the water chemistry by recharge from runoff near Buhl. Also, the sample site is more than 5 mi from the study area, as is the site for sample 13, and little weight was given to either in the chemical interpretations.

THERMAL GROUND-WATER DISCHARGE AND ASSOCIATED CONVECTIVE HEAT FLUX

Thermal ground-water discharge in the Banbury Hot Springs area was estimated for 26 wells and 2 springs. Water from these wells and springs is used for fish farming, swimming pools, therapeutic baths, space heating of

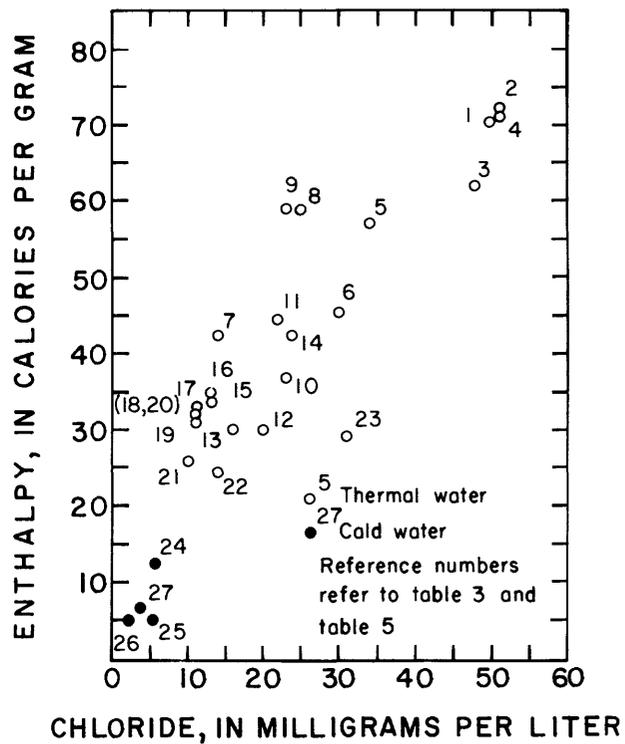


Figure 10. Relation of chloride to enthalpy.

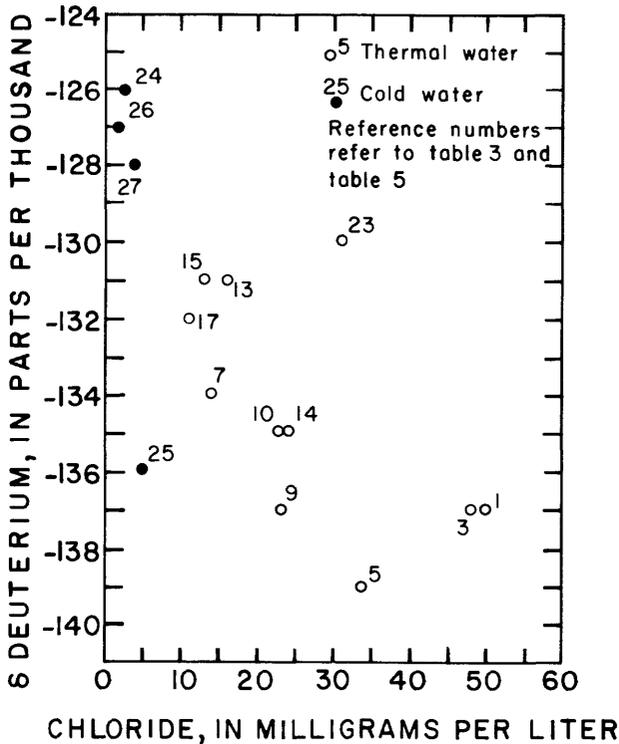


Figure 9. Relation of chloride to deuterium.

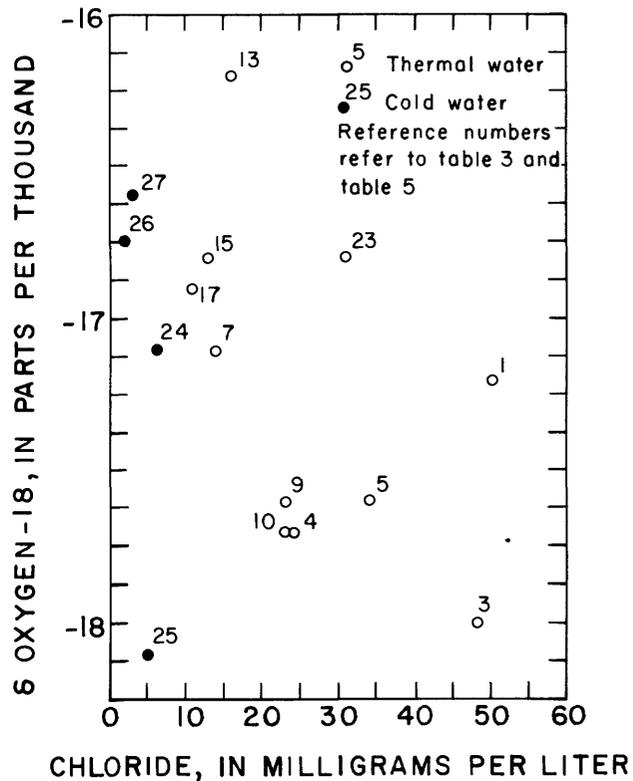


Figure 11. Relation of chloride to oxygen-18.

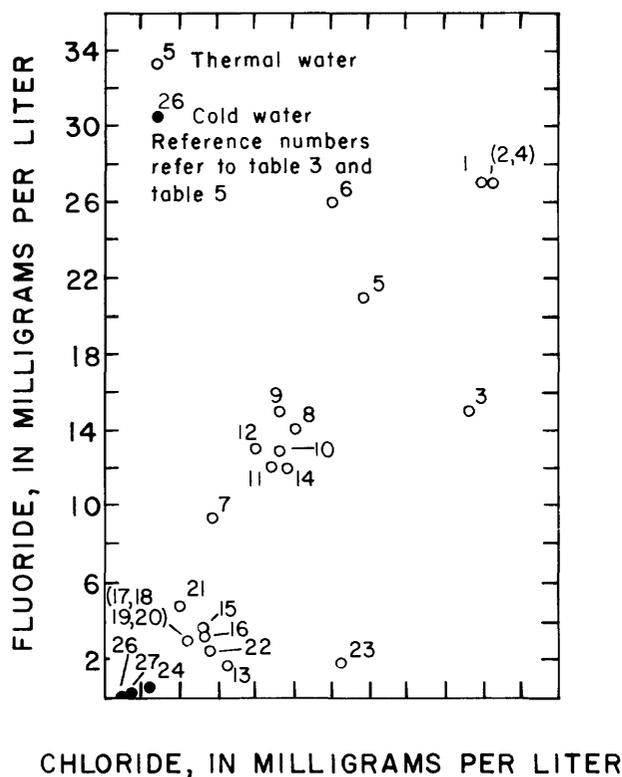


Figure 12. Relation of chloride to fluoride.

private residences, and a greenhouse. Ultimate discharge of the water produced by the thermal wells and springs is, primarily, into the Snake River. For purposes of this study, all thermal water withdrawn from wells and springs is considered to be consumptively used.

Measurements or estimates of discharge for all wells and springs in the study area were made in early 1979 (well discharges are shown in tables 1 and 2; spring discharges are shown in table 2). Selected wells were measured again late in the summer of 1979 to determine seasonal changes in water withdrawals. No significant seasonal change was observed. Withdrawal for each well and spring was estimated by the measured or estimated discharge and the period of use. Thermal ground-water discharge in the Banbury Hot Springs area in 1979 was about 10,300 acre-ft.

Heat from the Banbury Hot Springs area geothermal system is discharged convectively in thermal water, which discharges naturally from springs or artificially from flowing wells and one pumped well. The convective heat flux from the system can be calculated as the product of the volume rate of discharge and the enthalpy (heat content) of the water in excess of the ambient (surrounding) air temperature, or

$$H = M (h_r - h_o),$$

where

H = heat loss, by convection, in calories per second,

M = mass discharge,

h_r = enthalpy of thermal water, and

h_o = enthalpy of cold recharge water, at 10°C.

To estimate the total convective heat flux, the volume of thermal water discharge from each well or spring in 1979 was converted to an instantaneous flow rate, and the mass discharge, M, was calculated. In the above equation, h_o is taken as the mean annual air temperature, which is about 10°C for the study area. Once withdrawn, subsequent percolation of thermal water is considered negligible because, after the water is used, it is discharged to the Snake River by means of ditches or pipes, and no heat is returned to the system. Total convective heat flux from the Banbury Hot Springs area in 1979 was 1.1×10^7 cal/s.

AREAL EXTENT OF THE GEOTHERMAL RESERVOIR

For this study, the areal extent of the geothermal reservoir in the Banbury Hot Springs area can only be approximated. Surface evidence of the reservoir includes several thermal springs and numerous thermal wells. On the basis of the surface evidence, approximate areas where proven and potential low-temperature geothermal resources occur were delineated (fig. 13). As additional wells are drilled and new data become available, the approximate boundaries will, undoubtedly, be altered.

Most of the thermal wells and use of the resource occur near a northwest-trending fault that has been mapped in the area. Thermal water probably moves upward along this fault from depths below 4,400 ft to mix in varying proportions with cooler local ground water in a complex network of interconnected fractures. No thermal water occurs on the northeast side of the Snake River, and, for the purpose of this discussion, the general course of the river is considered an approximate boundary of the system. Thermal water occurs in wells to the northwest as far as the vicinity of Banbury Hot Springs Natatorium. Nearly 2 mi northwest of the natatorium, in the vicinity of Salmon Falls Creek, recently drilled wells produce water with temperatures as high as 72°C. The areal extent of the thermal water along Salmon Falls Creek is not well defined, due to lack of data. The northeastern boundary may be near well 8S-14E-19DAD1. This well was drilled to a depth of 700 ft, encountered water at a temperature of 30°C (markedly below other temperatures in the area), and had an artesian head slightly above land surface. Spring 8S-14E-31ACD1S, with a water temperature of 57°C at the surface, represents the southwestern surface expression of thermal water along Salmon Falls Creek. Chemical and isotopic data indicate that the 72°C water is probably representative of the deep-circulating component that mixes with cooler local ground water all along the Banbury system. Although

some connection to allow mixing is implied by the water chemistry, no wells presently indicate that thermal water occurs in the area between Salmon Falls Creek and the Banbury Hot Springs Natatorium.

Deep Creek marks the southeastern extent of current development in the Banbury system. Chemical analyses of 25° to 26°C water from two wells about 3 mi southeast of Deep Creek are similar to those of the Banbury thermal water. About 3 mi farther to the southeast, along an extension of one of the mapped faults, 29°C water is pumped from a well about 900 ft deep. The chemistry of the water from this well differs somewhat from that of the Banbury thermal water, but this may be due to mixing of recharge locally influenced by agricultural and urban development. Thermal water may occur in the areas between these existing warm-water wells; however, additional data are necessary to extend the southeastern

SUMMARY

Rocks underlying the Banbury Hot Springs area are of volcanic and sedimentary origin and range in age from late Miocene to Holocene. Thermal water, temperatures of which range from 30° to 72°C, issues from two springs and flows from numerous shallow wells bottomed chiefly in silicic volcanics and basalt. Presently, thermal water is beneficially used by residents for home heating, swimming pools, therapeutic baths, catfish and tropical fish production, and greenhouse operation.

Most wells are located in a narrow belt near or along the extension of a northwest-trending fault. Other northwest-trending faults southwest of the study area act as barriers to ground-water movement from the southwest. Artesian heads in wells range from slightly above to 360 ft above land surface. The hottest water (temperature near 72°C) occurs in the vicinity of Salmon Falls Creek. On the basis of available heat-flow data, depth of circulation in the system required to attain water temperatures near 70°C is about 4,400 ft. Because these temperatures occur in water from wells 420 to 700 ft deep, some convective transport of heat, probably upward along faults, is indicated.

Recorders installed on two wells to monitor pressure and flow at the well head indicate a decline in the artesian head from 164 to 146 ft between July 1979 and March 1980, and a decline in discharge from 3,110 to 1,550 gal/min between April 1979 and March 1980. Declines may reflect seasonal fluctuation or may represent reservoir response to development of the resource. Continued monitoring is necessary to determine the nature of the decline.

Thermal waters sampled are sodium carbonate or bicarbonate in character and are slightly alkaline

limits of the Banbury system continuously beyond Deep Creek.

Thermal water occurs in wells to the southwest only a short distance from the fault shown in the Banbury Hot Springs area (fig. 1), and the extent of the geothermal system to the southwest is unknown. Water temperatures in wells south of the Banbury area and east of Salmon Falls Creek range between 11° and 14°C. No data are available to indicate whether thermal water occurs below the cooler ground-water system.

West of Salmon Falls Creek, 9 to 12 mi southwest of the Banbury area, the temperature of water from three wells ranged from 24.5° to 30°C. Chemical analyses show a similarity of the water to thermal ground water in the regional system, and it is not likely that this water is associated with the thermal water in the Banbury Hot Springs area.

(pH, 7.9–9.5). A general increase in concentrations of chloride, fluoride, and boron occurs with an increase in temperature. Relations of chloride with deuterium, oxygen-18, enthalpy, and fluoride and between stable isotopes of oxygen-18 and deuterium indicate a mixing of hot water from a single deep source with shallow cooler local ground water to give the range of temperature and chemical makeup evident in the Banbury thermal waters. Concentrations of tritium in samples indicate that most thermal water contained little or no post-1954 water and is probably at least 100 years old and perhaps more than 1,000 years old. One sample of 33°C water contained 4.1 ± 0.2 TU and may have had a residence time of only 29 years.

Probable maximum reservoir temperatures, estimated by using the silica and the Na-K-Ca geothermometers, are generally between about 70° and 100°C. The sulfate-water geothermometer indicates that maximum reservoir temperatures in the Banbury system are probably near 90°C.

Measurements or estimates of discharge for all wells and springs in early 1979 indicated a total thermal water discharge of 10,300 acre-ft annually. Heat, which is removed from the Banbury system in the thermal water discharge, amounted to 1.1×10^7 cal/s in 1979.

Proven areas of low-temperature geothermal resources (where thermal water is being removed and used beneficially) are near or along an extension of a northwest-trending fault. Potential areas of low-temperature geothermal resources lie between the proven areas along or near the same fault.

EXPLANATION



Approximate proven area of low-temperature geothermal water



Approximate potential area of low-temperature geothermal water

----- Fault - Dashed where approximately located; dotted where concealed.
U, upthrown side; D, downthrown side (Malde, Powers, and Marshall, 1963; and Malde and Powers, 1972)

areas of low-temperature geothermal water.

SELECTED REFERENCES

- Brook, C. A., and others, 1979, Hydrothermal convection systems with reservoir temperatures $\geq 90^{\circ}\text{C}$, in Muffler, L. J. R., ed., Assessment of geothermal resources of the United States: U.S. Geological Survey Circular 790, 163 p.
- Craig, Harmon, 1963, The isotopic geochemistry of water and carbon in geothermal areas, in Tongiori, E., ed., Spollette Conference on Nuclear Geology and Geothermal Areas, Spollette, 1963: Rome, Consiglio Nazionale delle Recerche, 17 p.
- Ellis, A. J., and Mahon, W. A. J., 1977, Chemistry and geothermal systems: New York, Academic Press, 392 p.
- Fournier, R. O., and Potter, R. W. II, 1979, Magnesium correction to the Na-K-Ca chemical geothermometer: *Geochimica et Cosmochimica Acta*, v. 43, p. 1543-1550.
- Fournier, R. O., and Rowe, J. J., 1966, Estimates of underground temperature from silica content of water from hot springs and wet steam wells: *American Journal of Science*, v. 264, p. 685-695.
- Fournier, R. O., Sorey, M. L., Mariner, R. H., and Truesdell, A. H., 1979, Chemical and isotopic prediction of aquifer temperatures in the geothermal system at Long Valley, California: *Journal of Volcanology and Geothermal Research*, v. 5, p. 17-34.
- Fournier, R. O., and Truesdell, A. H., 1973, An empirical Na-K-Ca geothermometer for natural waters: *Geochimica et Cosmochimica, Acta*, v. 36, p. 1255-1275.
- Fournier, R. O., White, E. D., and Truesdell, A. H., 1974, Geochemical indicators of subsurface temperature, Part 1, Basic assumptions: *U.S. Geological Survey Journal of Research*, v. 2, no. 3, p. 259-262.
- Gat, J. R., 1971, Comments on the stable isotope method in regional groundwater investigations: *Water Resources Research*, v. 7, no. 4, p. 980-993.
- Kharaka, Y. K., and Barnes, Ivan, 1973, SOLMNEQ—solution-mineral equilibrium computations: Menlo Park, Calif., U.S. Geological Survey Computer Contributions, 82 p.
- Malde, H. E., and Powers, H. A., 1972, Geologic map of the Glenns Ferry-Hagerman area, west-central Snake River Plain, Idaho: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-696, 2 sheets.
- Malde, H. E., Powers, H. A., and Marshall, C. H., 1963, Reconnaissance geologic map of west-central Snake River Plain, Idaho: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-373, 1 sheet.
- McKenzie, W. F., and Truesdell, A. H., 1977, Geothermal reservoir temperatures estimated from the oxygen isotope compositions of dissolved sulfate and water from hot springs and shallow drill holes: *Geothermics*, v. 5, p. 51-61.
- Nehring, N. L., and others, 1979, Sulfate geothermometry of thermal springs in the western United States: U.S. Geological Survey Open-File Report 79-1135, 11 p.
- Nir, A., 1964, On the interpretation of tritium "age" measurements of groundwater: *Journal of Geophysical Research*, v. 69, no. 12, p. 2589-2595.
- Pearson, F. J., and Truesdell, A. H., 1978, Tritium in the waters of the Yellowstone National Park, in Zartman, R. F., ed., Short Papers of the Fourth International Conference, Geochronology, Cosmochronology, Isotope Geology, 1978, Colorado, August 20-25, 1978: U.S. Geological Survey Open-File Report 78-701, p. 327-329.
- Ross, S. H., 1971, Geothermal potential of Idaho: Moscow, Idaho, Idaho Bureau of Mines and Geology Pamphlet 150, 72 p.
- Schoen, Robert, 1972, Hydrochemical study of the National Reactor Testing Station, Idaho, in *Hydrogeology, International Geology Congress, 24th, Montreal, Section 11*: p. 306-314.
- Stearns, N. D., Stearns, H. T., and Waring, G. A., 1937, Thermal springs in the United States: U.S. Geological Survey Water-Supply Paper 679-B, 200 p.
- Young, H. W., and Lewis, R. E., 1980, Hydrology and geochemistry of thermal ground water in southwestern Idaho and north-central Nevada: U.S. Geological Survey Open-File Report 80-2043, 40 p.
- Young, H. W., and Mitchell, J. C., 1973, Geothermal investigations in Idaho, Part 1, Geochemistry and geologic setting of selected thermal waters: Idaho Department of Water Resources Water Information Bulletin no. 30, 43 p.

Conversion Factors

The following conversion table is included for the convenience of those who prefer to use SI (International System of Units) rather than the inch-pound system of units. Chemical data for concentrations are given only in mg/L (milligrams per liter) or $\mu\text{g/L}$ (micrograms per liter) because these values are, within the range of values presented, numerically equal to parts per million or parts per billion, respectively. Thermal parameters are reported in "working" units.

Multiply inch-pound unit	by	To obtain SI unit
<u>Length</u>		
inch (in)	25.40	millimeter
foot (ft)	0000.3048	meter
mile (mi)	1.609	kilometer
<u>Area</u>		
acre	4047	square meter
square mile (mi ²)	2.590	square kilometer
<u>Volume</u>		
acre-foot (acre-ft)	1233	cubic meter
<u>Flow</u>		
gallon per minute (gal/min)	0.06309	liter per second
Multiply working unit	by	To obtain SI unit
<u>Heat Flow</u>		
microcalorie per square centimeter · second [$\mu\text{cal}/(\text{cm}^2 \cdot \text{s})$] heat flow unit (HFU)	4.187×10^{-2}	watt per square meter
<u>Thermal Conductivity</u>		
millicalorie per centimeter second · degree [$\text{mcal}/(\text{cm} \cdot \text{s} \cdot ^\circ\text{C})$]	0.4187	watt per meter · degree kelvin
<u>Heat Discharge</u>		
calorie per second (cal/s)	4.187	watt
<u>Energy</u>		
calorie (cal)	4.187	joule

Conversion of $^\circ\text{C}$ (degrees Celsius) to $^\circ\text{F}$ (degrees Fahrenheit) is by the equation: $^\circ\text{F} = (1.8)(^\circ\text{C}) + 32$. Water temperatures are reported to the nearest one-half degree.

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