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Determination of uranium in source rocks by using radium in Crystal Springs, Great Salt Lake area, Utah

By

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Abstract

Measurements of radium in 15 mineral springs in the Great Salt Lake area show that Crystal Springs, located on a fault bordering the west edge of the Wasatch Range north of Brigham City, has the highest radium content, 220 µµg/l. Other springs within 20 km west of the Wasatch Range have radium contents of 20-140 µµg/l. The areal distribution of radium and other elements such as barium, iron, manganese, and copper, in water and chemical precipitates combined with the known geology indicates that these springs are associated with faults and possibly with hydrothermal mineral deposits in the fault systems.

The quantity of radium in the water at Crystal Springs was used to calculate an amount of uranium in the rocks through which water flows to the spring. The calculations are based on the fact that radium, as a daughter product of uranium, is produced at a known rate based on radioactive decay and requires a certain amount of uranium in the system for its production. By using decay rates and equilibrium relationships, the amount of uranium required was determined to be at least 5.2×10^9 g, or 5,200 metric tons. If the uranium is concentrated in fractures and adjacent rocks comprising 0.01 percent of the estimated 10^{16} g of rock in the Crystal Springs system, then 10^{12} g of rock could contain an average of 0.52 percent uranium.

Introduction

The use of hydrogeochemical techniques in exploration for U deposits has attracted much interest in the last few years. Where ground water is concerned, the common approach is to sample springs and wells in a sedimentary depositional basin in an attempt to outline areas of locally anomalous U in aquifers that might be related to tabular or roll-type U deposits. In other geologic terranes and in sedimentary environments characterized by post-Mesozoic tectonic activity, some ground water rises to the surface along permeable fault zones and issues as hot or warm mineral springs. Theoretically, at least, such springs may be related to hydrothermally deposited vein minerals which may constitute economic resources. Springs that contain significant amounts of U or Ra may indicate the presence of U-bearing veins at depth.

While much is known about the behavior of U in the aqueous environment, less is known about Ra—a moderately long lived daughter product of U and the immediate daughter of Th^{230}. (Unless otherwise noted, U refers to U^{238} and Ra refers to Ra^{226} in the decay of U^{238} to Th^{234}, Pa^{234}, U^{234}, Th^{230}, Ra^{226}, Rn^{222}, and so on to Pb^{206}.) Unlike U, Ra is an alkaline earth element not subject to oxidation-reduction reactions and not known to form complexes with other ions in solution. Ra is commonly thought to be immobile relative to U (Davis and DeWiest, 1966, p. 136). However, analyses from springs and wells that we have sampled in Colorado, Utah, Arizona, and New Mexico show that Ra is frequently present in ground water in amounts far exceeding the equilibrium amount for the U present. Also, isotopic analyses (U^{238},

U^{234}, Th^{230}, Ra^{226}, Rn^{222}, and Th^{232}) of hot springs in several Western States (O'Connell and Kaufmann, 1976) show that Ra commonly exceeds the equilibrium amount for Th^{230} as well as for U. U is relatively mobile in oxidizing slightly alkaline bicarbonate-rich ground water or in acid sulfate-rich water. On the other hand, Ra is more mobile in chloride-rich reducing ground water (Tokarev and Scherbakov, 1960, p. 63, 66, 99-100; Tanner, 1964, p. 268-270). Because of its distinctive geochemical behavior, Ra has potential for being used to indicate U deposits in environments not conducive to the use of U in water. The Ra content of springs containing Ra in amounts several hundred times the equilibrium amount for the U in the water can be used to calculate the amount of U needed to produce that Ra. The U minerals may be disseminated over a large area or concentrated in economically significant deposits in more restricted areas. The possibility is strong that Ra in mineral springs associated with faults is derived, at least in some instances, from concentrated U in the underlying fracture system by water which favors the mobility of Ra over U or Th^{230}.

In this paper, the amount of U in source rock that would be required to produce the Ra in the water at Crystal Springs, north of Brigham City, Utah, was calculated in order to determine whether the source rock may have a potential for U concentrations of economic interest. Crystal Springs is one of several springs in the Great Salt Lake area which contain Ra in amounts which exceed equilibrium for the U present.

Sample collection and analysis

Reconnaissance sampling in Colorado, Utah, Arizona, and New Mexico in 1975-76 indicated several areas worthy of further investigation (Cadigan and Felmlee, 1977). One of these areas is near the Great Salt Lake in the Basin and Range Province of Utah. (fig. 1). This area was revisited in May 1976. Water samples were collected from 11 springs for major-element wet chemical analysis, minor-element emission spectrographic analysis, and Ra and U radiochemical analysis. Ra and (or) U analyses and limited major- and minor-element data are available (O'Connell and Kaufmann, 1976; Mundorff, 1970) for water from 4 other springs, making a total of 15 sites for which at least some radioactivity data are known (fig. 2 and table 1). Samples of chemically precipitated deposits were collected from 8 of the 15 sites for semiquantitative spectrographic analysis and beta-gamma equivalent uranium count (table 2).

Discussion of analytical results

Although all of the water samples are of the NaCl type, they do exhibit a range of values for concentrations and percentages of the major ions (fig. 3). (See Hem, 1970, p. 264-270, or Hall, 1963, p. 163-164, for discussion of water classification.) Morgan Ranch Warm Spring is fresh and has the most SO_4, HCO_3, Ca, and Mg of all the samples; Salt Springs and Baker Spring at Locomotive Springs are slightly saline and also have relatively large percentages of these ions. Water at these three widely separated sites is believed to contain large contributions of relatively fresh water from shallow aquifers. Samples from Wasatch, Hooper, and Becks Hot Springs near the Wasatch Range are moderately saline to very saline but contain enough SO_4, HCO_3, Ca, and Mg to

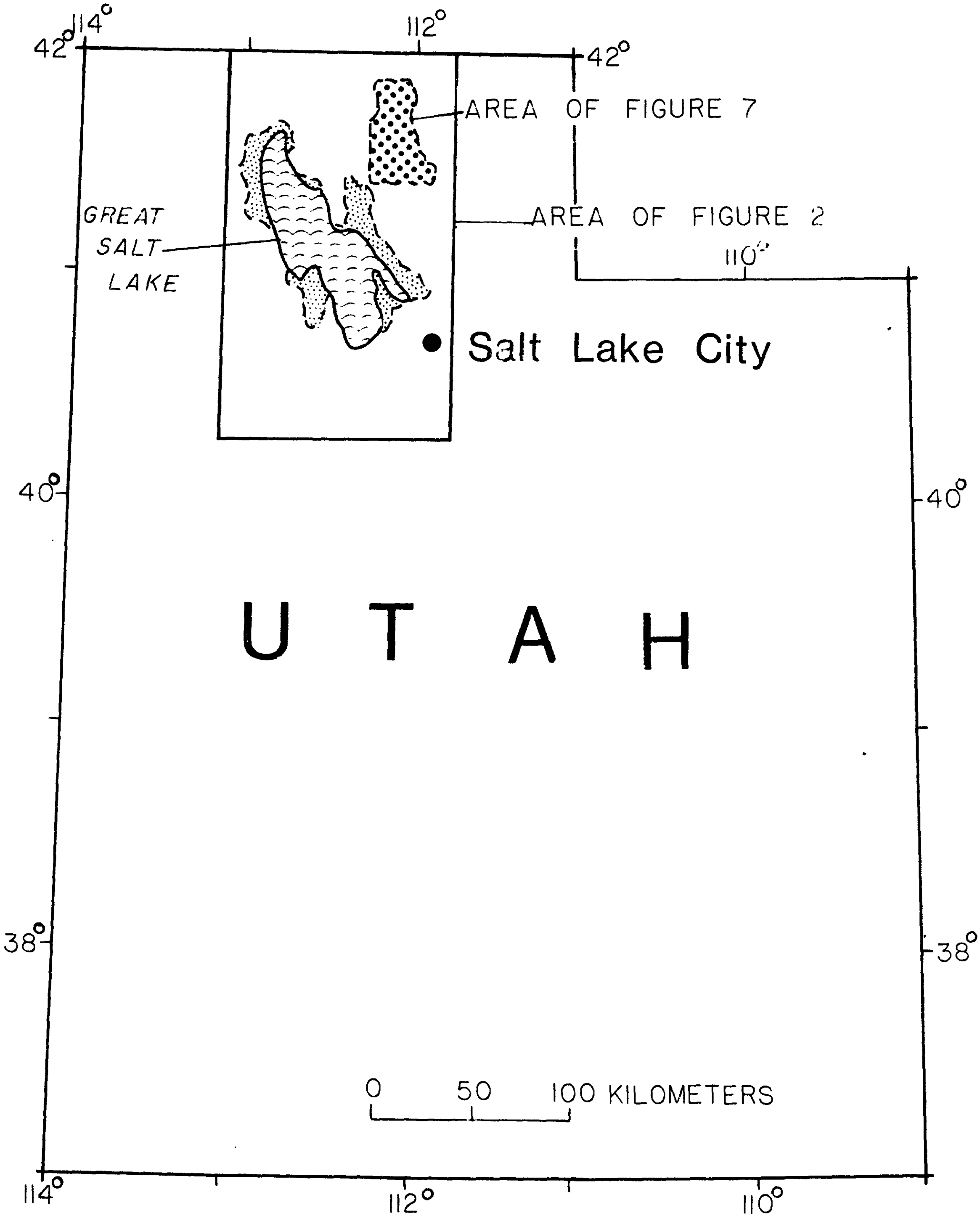

Figure 1.--Index map of study area. Outer lake perimeter is 1958 level; inner is 1965 level.

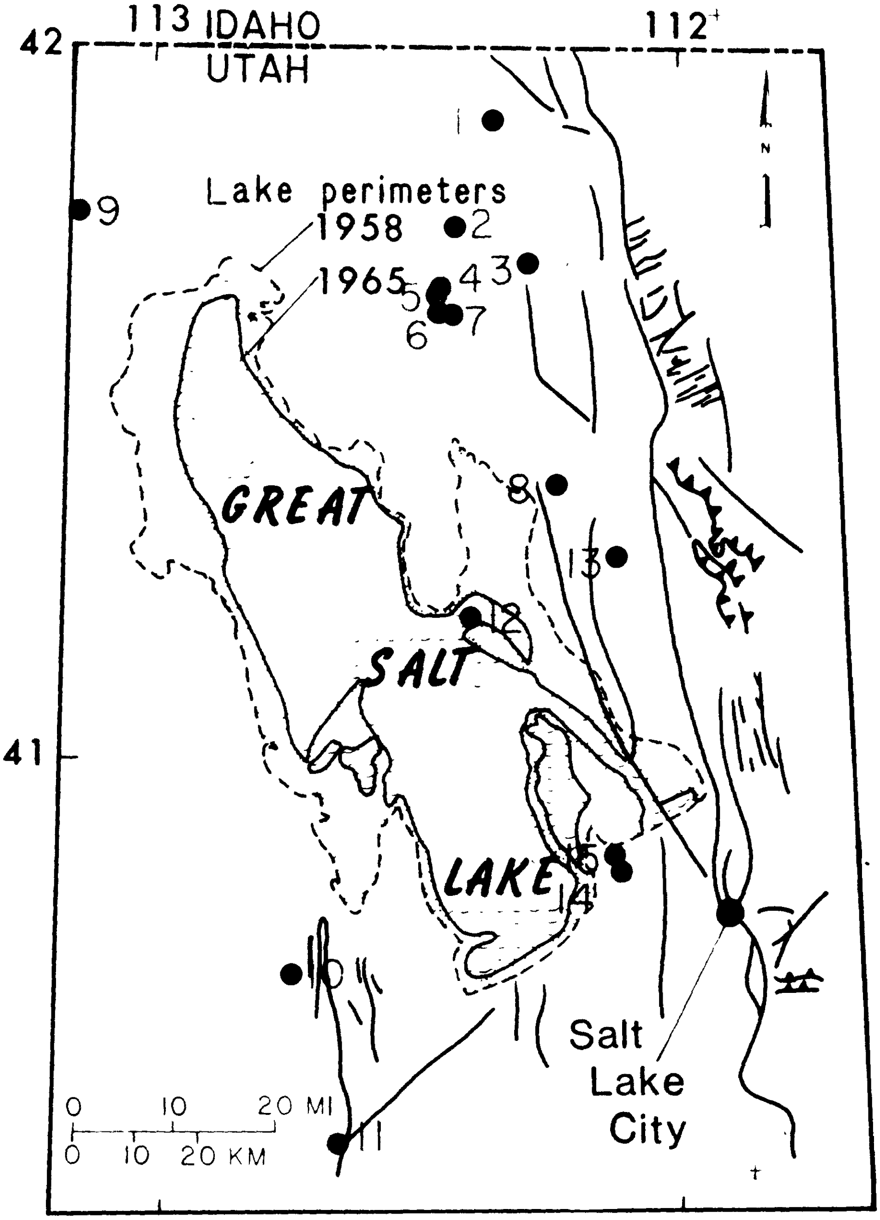

Figure 2.- Sample locations

1. Udy Hot Springs
2. Salt Springs
3. Crystal Springs
4. Poison Spring
5. Painted Rock Spring
6. Little Mountain hot spring
7. Stinking Hot Springs
8.- Utah Hot Springs
9.- Locomotive Springs
10.- Grantsville Warm Springs
11.- Morgan Ranch Warm Springs
12.- Hooper Hot Springs
13.- Ogden Hot Springs
14.- Wasatch Hot Springs
15.- Becks Hot Springs

Heavy lines (toothed for thrust) indicate faults.
Faults are modified from Stokes (1964), Bjorklund and McGreevy (1974), Mundorff (1970), Thomas and Nelson (1948), and Thomas (1946).

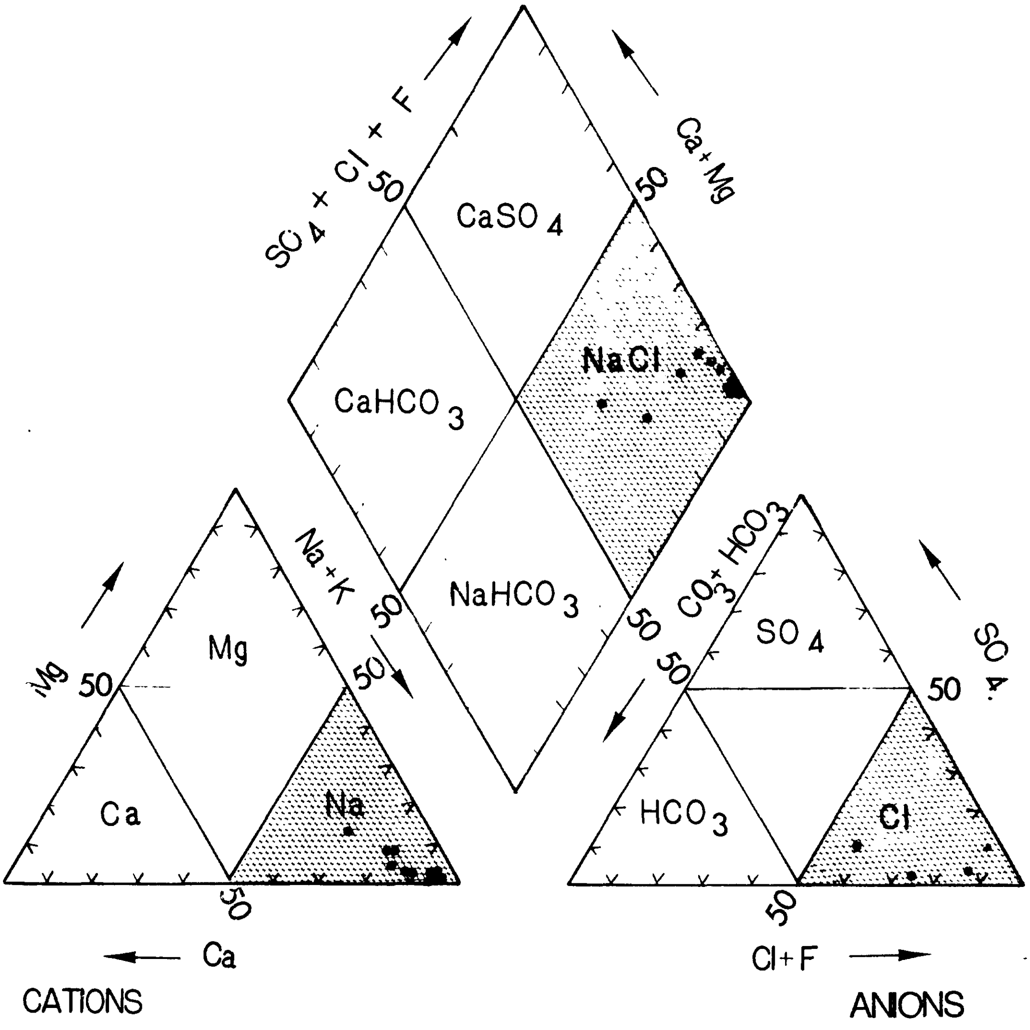

Figure 3.- Water types. Values are percentage in equivalents per million.

Table 1.--Analyses of spring waters

[Ra determined by coprecipitation and alpha count (radon method); U, by extraction fluorometry; major ions, by wet chemical methods; minor elements, by emission spectrography. pH and temperature were measured in the field. *, analysis from Mundorff (1970); +, analysis from O'Connell and Kaufmann (1976)]

Sample	Ra (uug/l)	U (ug/l)	Dissolved solids (mg/l)	Temperature (°C)	pH	SiO_2 (mg/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Cl (mg/l)	HCO_3 (mg/l)
St----	75 76 120 80+	0.01	27900	43	6.6	36	740	330	9000	490	17000	443
Li----	53	1.5	35100	43	6.8	24	700	220	12000	590	21000	530
Cr----	220 410+	1.5	43500	56	6.3	27	800	180	15000	780	26000	471
Ud----	32	.8	8590	51	7.5	25	220	56	2900	140	5000	302
Ut----	66 140+	.04	20400	54	7.4	33	910	25	6300	870	12000	195
Pa----	2.9	2.0	9240	16	7.4	22	210	110	3100	120	5400	261
Po----	3.1	1.7	13400	20	7.8	27	260	150	4700	200	7700	310
Gr----	5.0	1.4	20500	17	7.9	33	510	130	6900	220	12000	253
Mo----	.26	.5	574	25	8.0	19	54	24	110	12	180	173
Lo----	.09	2.7	2170	15	8.1	37	110	53	500	38	960	210
Sa----	.30	1.9	1130*	16*	7.6*	17*	74*	35*	310*	17*	490*	282*
Be----	23+	--	13900*	56*	7.4*	32*	746*	131*	4250*	156*	7470*	221*
Wa----	27+	--	6000*	41*	7.9*	16*	433*	90*	1620*	70*	2820*	244*
Ho----	74 62+	.08	8230*	48*	7.6*	30*	506*	91*	2350*	256*	4840*	224*
Og----	21 23+	.28	8680*	57*	7.7*	45*	320*	49*	2690*	347*	4990*	192*

Table 1.--Analyses of spring waters--Continued

[Leaders indicate not analyzed for]

Sample	SO_4 (mg/l)	NO_3 (mg/l)	PO_4 (mg/l)	Al (ug/l)	Ba (ug/l)	B (ug/l)	Fe (ug/l)	Li (ug/l)	Mo (ug/l)	Sr (ug/l)	Zn (ug/l)	Mn (ug/l)	F (mg/l)
St----	79	0.04	0.09	1400	7600	3100	400	4800	160	30000	30	<100	0.9
Li----	300	.16	.08	870	400	4000	1500	5600	380	32000	40	<100	1.4
Cr----	470	.11	.09	1200	400	4000	1300	7100	380	38000	50	<150	1.3
Ud----	95	.01	.03	150	4500	800	200	1300	100	9300	30	<30	1.2
Ut----	180	.02	.06	370	500	2800	5000	9800	260	24000	20	1700	3.7
Pa----	130	3.4	.03	130	200	1000	<20	1400	90	13000	30	<30	.7
Po----	180	1.4	.05	200	100	1500	100	2100	110	11000	40	<50	.9
Gr----	570	.01	.07	270	100	1100	<50	2300	170	8000	40	90	.8
Mo----	88	.04	.01	20	70	180	<20	40	10	1500	<1	3	1.1
Lo----	90	.63	.02	50	70	200	20	220	20	3500	<1	<10	.4
Sa----	39*	1.7*	.01	20*	50	150*	0*	150*	15	1700	<1	<10*	.4*
Be----	985*	.7*	--	31*	--	1200*	37*	2300*	<.3*	--	<5.7*	486*	3.3*
Wa----	818*	7.3*	--	--*	--	900*	--*	780*	--*	--	--*	--*	2.8*
Ho----	38*	1.9*	--	34*	--	1100*	137*	2000*	<.3*	--	<5.7*	3000*	1.0*
Og----	121*	.9*	--	69*	--	2600*	154*	3500*	<.3*	--	<5.7*	914*	3.8*

Samples

St, Stinking Hot Springs	Pa, Painted Rock Springs	Sa, Salt Springs
Li, Little Mountain hot springs	Po, Poison Spring	Be, Becks Hot Springs
Cr, Crystal Springs	Gr, Grantsville Warm Springs	Wa, Wasatch Hot Springs
Ud, Udy Hot Springs	Mo, Morgan Ranch Warm Springs	Ho, Hooper Hot Springs
Ut, Utah Hot Springs	Lo, Locomotive Springs	Og, Ogden Hot Springs

Table 2.--Analyses of spring precipitates

[eU determined by beta-gamma scaler; RaeU, by gamma-ray spectrometry; U and Th, by delayed neutron techniques; all other elements, by six-step semi-quantitative spectrography. All values are in parts per million. G, greater than; N, not detected at limit shown; L, detected as poorly defined emission line below limit of detection. Not detected at limits shown: Ag, 0.5; As, 1000; Au, 20; Bi, 10; Cd, 50; La, 50, Nb, 10; Pd, 2; Pt, 50; Sb, 200; Sc, 5; Sn, 10; Te, 2000; U, 500; P, 2000; Ce, 200; Li, 100. Analysts: A. J. Bartel, C. M. Bunker, C. A. Bush, I. C. Frost, J. P. Hemming, J. O. Kelley, R. J. Knight, H. T. Millard, H. G. Neiman, B. White. Leaders indicate not analyzed for.]

Sample	eU	RaeU	U	Th	Fe	Mg	Ca	Ti	Mn	B	Ba	Be	Co	Cr	Cu
St 1---	10200	17000	--	--	500	300	5000	70	7	20N	100000G	1N	5N	5	1
St 2---	6010	8500	0.2N	4N	700	3000	100000G	70	100	20N	100000G	1N	5N	2	2
St 3---	710	1250	.2	4N	3000	7000	100000G	700	200	20N	100000	1N	5N	20	15
St 4---	590	1300	1.2	4N	5000	20000	100000G	700	150	30	70000	1N	5N	30	10
St 5---	130	--	--	--	7000	20000	100000G	500	100	20	20000	1N	5N	30	300
Ud 1---	20	--	--	--	5000	7000	100000G	700	100	20N	500	1N	5N	20	15
Ud 2---	20	--	--	--	5000	3000	100000G	200	100	20N	500	1N	5N	20	1.5
Cr-----	110	--	--	--	20000	10000	100000G	200	50	20N	2000	1	5N	15	5
Pa-----	10	--	--	--	5000	15000	100000G	300	1000	20N	700	1N	5N	10	7
Po-----	10N	--	--	--	3000	7000	100000G	200	150	50	200	1N	5N	10	7
Ut 1---	1050	5700	--	--	100000G	700	100000G	20	5000	20N	2000	100	5N	5	1
Ut 2---	410	1230	--	--	50000	1000	100000G	70	20000	30	1500	20	5N	1	5
Ut 3---	80	--	--	--	50000	200	100000G	2N	10000	20N	1000	20	5N	1N	1N
Og-----	430	460	.2	4N	50000	2000	100000G	300	10000	20N	1000	15	5N	15	5
Gr 1---	410	--	--	--	10000	5000	100000G	100	10000	20N	1000	1N	10	3	5
Gr 2---	30	--	--	--	3000	5000	100000G	100	3000	20N	100	1N	15	10	20

Table 2.--Analyses of spring precipitates--Continued

Sample	Mo	Ni	Pb	Sr	V	W	Y	Zn	Zr	Si	Al	Na	K	Ga	Ge	Yb	Tl
St 1---	3N	3N	10N	10000	7L	100N	10N	500	10N	15000	3000	2000	7000N	5N	10N	1N	--
St 2---	3N	3N	10N	15000	7N	100N	10N	300N	30	5000	2000	500N	7000N	5N	10N	1N	--
St 3---	3N	3N	10N	7000	15	100N	10L	300N	50	50000	15000	10000	7000N	5L	10N	1L	--
St 4---	3N	3	20	7000	30	100N	10	300N	70	70000	20000	15000	7000N	5	10N	1	--
St 5---	3N	3	15	700	10	100N	15	300N	50	100000G	20000	50000	15000	7	10N	1.5	--
Ud 1---	3N	3	10	15000	10	100N	15	300N	70	70000	30000	15000	10000	7	10N	1.5	--
Ud 2---	3N	3N	10N	2000	7	100N	10N	300N	10	15000	15000	5000	7000N	5N	10N	1N	--
Cr-----	3N	3	10	2000	7L	100N	10N	300N	30	50000	10000	30000	7000	5	10N	5	--
Pa-----	3N	7	10N	1000	10	100N	10N	300N	50	20000	10000	5000	7000N	5N	10N	1N	--
Po-----	3L	3L	10	1500	7L	100N	15	300N	50	50000	10000	70000	7000	5N	10N	1N	--
Ut 1---	7	3N	10N	1000	7N	100N	10N	300N	10N	15000	3000	10000	7000N	5N	50	1N	--
Ut 2---	7	3N	10N	5000	7N	100N	10N	300N	10N	10000	1500	30000	7000N	5N	30	1N	50L
Ut 3---	3N	3N	10N	3000	7N	100N	10N	300N	10N	5000	200	20000	7000N	5N	20	1N	--
Og-----	3N	3	10N	2000	10	100N	20	300N	30	50000	15000	5000	7000	5L	10	2	--
Gr 1---	7	15	10N	1000	10	100N	10N	300N	10N	15000	7000	15000	7000N	5N	10N	1N	--
Gr 2---	3N	70	30	1000	7	100L	10N	500	10	10000	5000	20000	7000N	5N	10N	1N	--

Samples

St, Stinking Hot Springs
Ud, Udy Hot Springs
Cr, Crystal Springs
Pa, Painted Rock Springs
Po, Poison Spring
Ut, Utah Hot Springs
Og, Ogden Hot Springs
Gr, Grantsville Warm Springs

distinguish them from the more purely NaCl samples and to indicate a contribution from relatively fresh water. All nine of the other samples are moderately saline to briny and contain 93-96 percent Na and K and 96-98 percent Cl in the dissolved fraction. These springs are believed to come from deeper sources where the water has had time to accumulate salts and may have come in contact with deep veins.

Ra is highest in springs closer to the Wasatch Range (fig. 4). Three springs have at least one analysis where Ra exceeds 100 μμg/l or pCi/l. Crystal Springs has the most Ra, 220-410 μμg/l. Other springs near the Wasatch Range have moderately high Ra, 20-140 μμg/l. Some springs contain <1 μμg/l.

Ra in the water has a high positive correlation with total dissolved solids and with most of the major and minor ions (fig. 5); in other words, the occurrence of Ra in the water seems to be influenced largely by the total ionic strength of the water. By comparison, U has a low correlation (0.10) with dissolved solids. The correlation coefficient between Ra and total dissolved solids is 0.76, thus, 58 percent of the variability in Ra can be attributed to variability in dissolved solids content. This leaves 42 percent of the variance unexplained, however. Some samples having relatively high salinity--such as Grantsville, Painted Rock, and Poison Springs--have low Ra, only 2-5 μμg/l. Such deviations reflect variations in unmeasured parameters that affect the Ra content of the water. Perhaps our sampling was biased toward springs reflecting above-background U in source rocks. The water in these three springs may flow through rocks which have only a small, background amount of Ra, represented by the lower dashed line

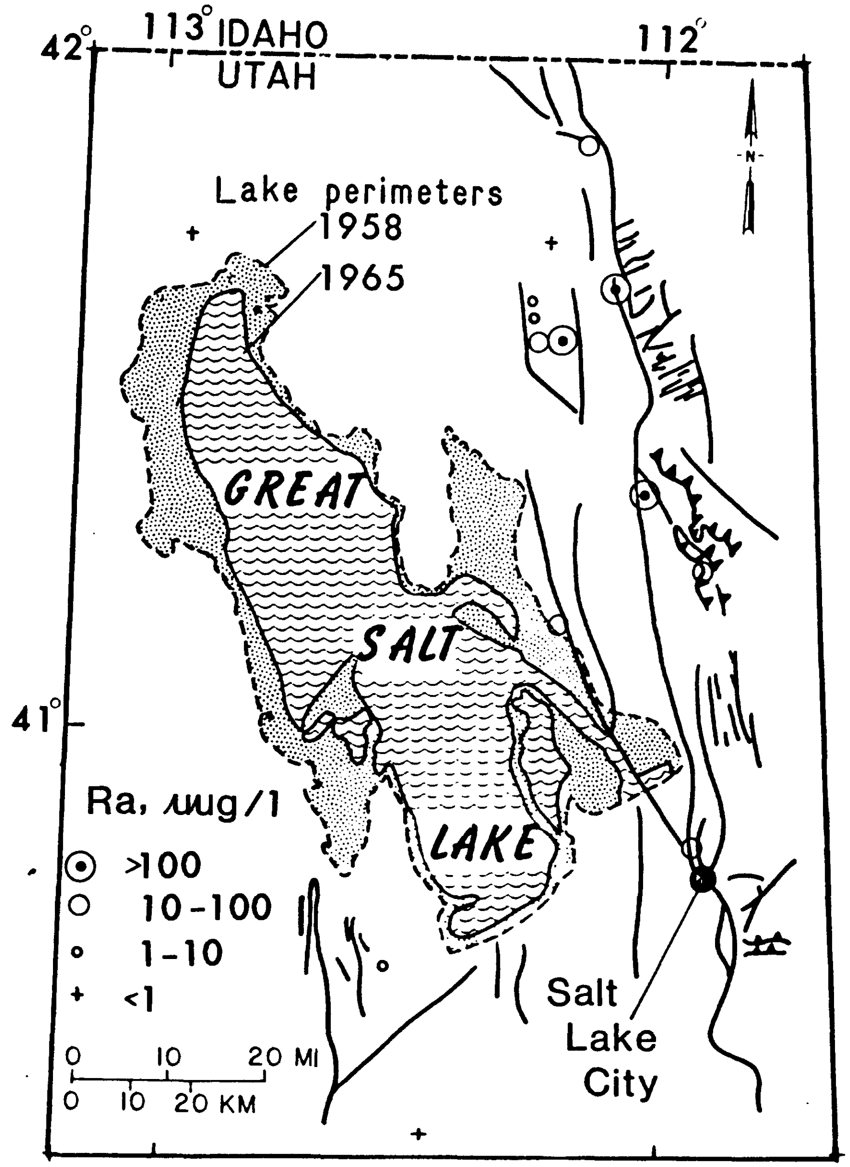

Figure 4.- Radium content of spring waters.

in figure 5, whereas the water in the other springs of comparable salinity flows through rocks which have above-average amounts of Ra, represented by the upper dashed line. More samples are needed to delineate these two populations with certainty.

Ba, Cu, Fe, and Mn are unusually abundant in the precipitates at some localities--notably, Ba and Cu at Stinking Hot Springs and Fe and Mn at Utah Hot Springs (fig. 6). The occurrence of such precipitates at some springs near the Wasatch Range but not at others which lie along parallel faults and have similar salinity indicates the influence of unmeasured parameters. These precipitates probably reflect local variations in the composition of the rocks in and near the fault systems from which the springs issue. Ba and Fe minerals are known to be associated with hydrothermal mineral deposits.

Moderately high Ra in many of the mineral springs near the Wasatch Range has combined with Ba at Stinking Hot Springs and Fe at Utah Hot Springs to produce very radioactive precipitates at these two sites. Lack of sufficient Ba or Fe in the water at Crystal Springs has resulted in an absence of such precipitates, even though Crystal Springs exceeds the other two sites in its Ra content.

Calculation of uranium in source rocks

Crystal Springs is several hundred times enriched in Ra relative to U; that is, the amount of Ra in the water exceeds by several hundred times the amount of Ra that would be in equilibrium with the amount of U in the water. This factor of several hundred, called the radium enrichment factor (REF), can be calculated by using the known equilibrium ratio for the Ra and U isotopes (1 g U/3.4 x 10^{-7}g Ra

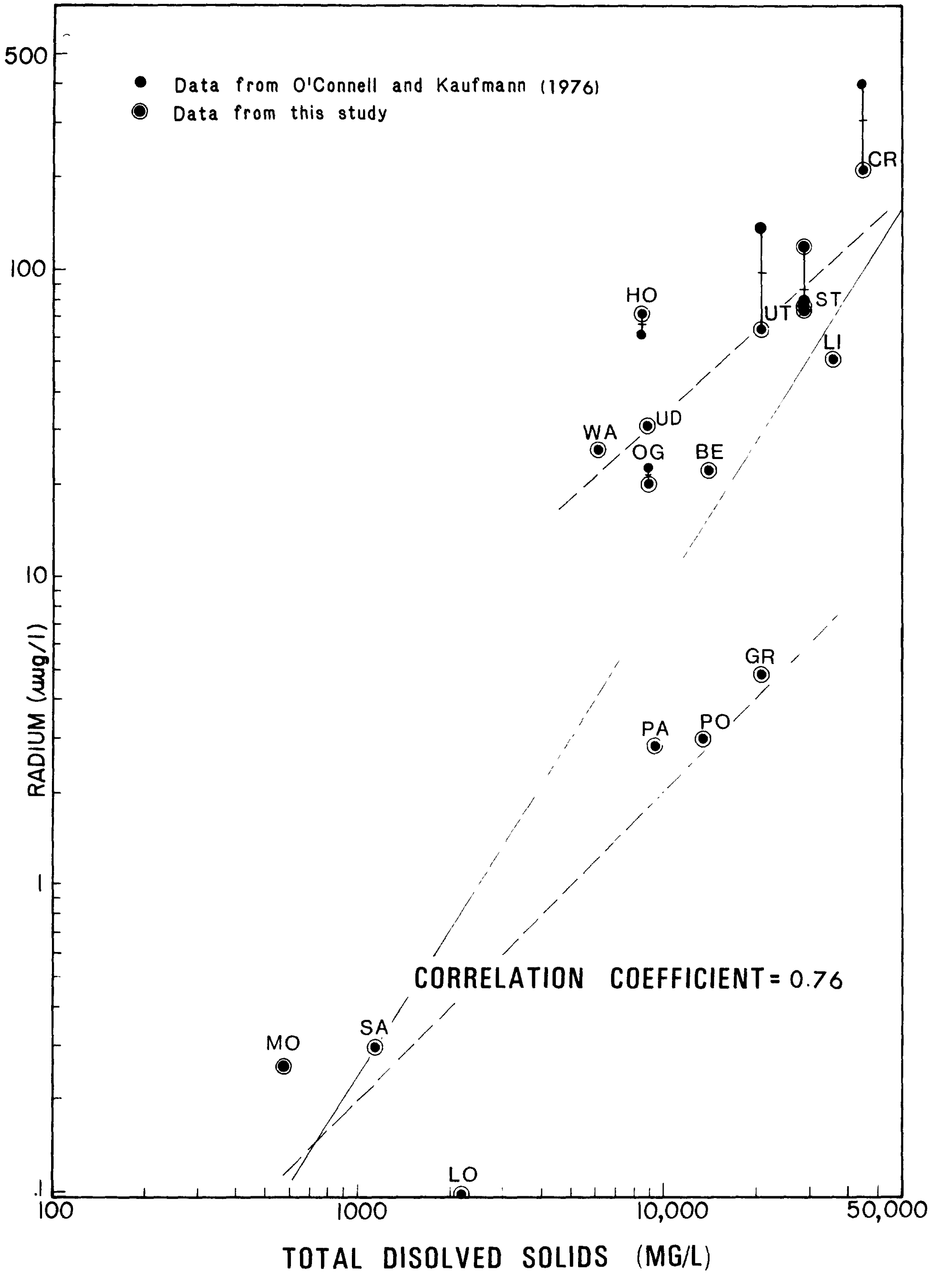

Figure 5.--Relationship between Ra and total dissolved solids contents of spring waters. Letters identify the springs, as abbreviated in Table 1.

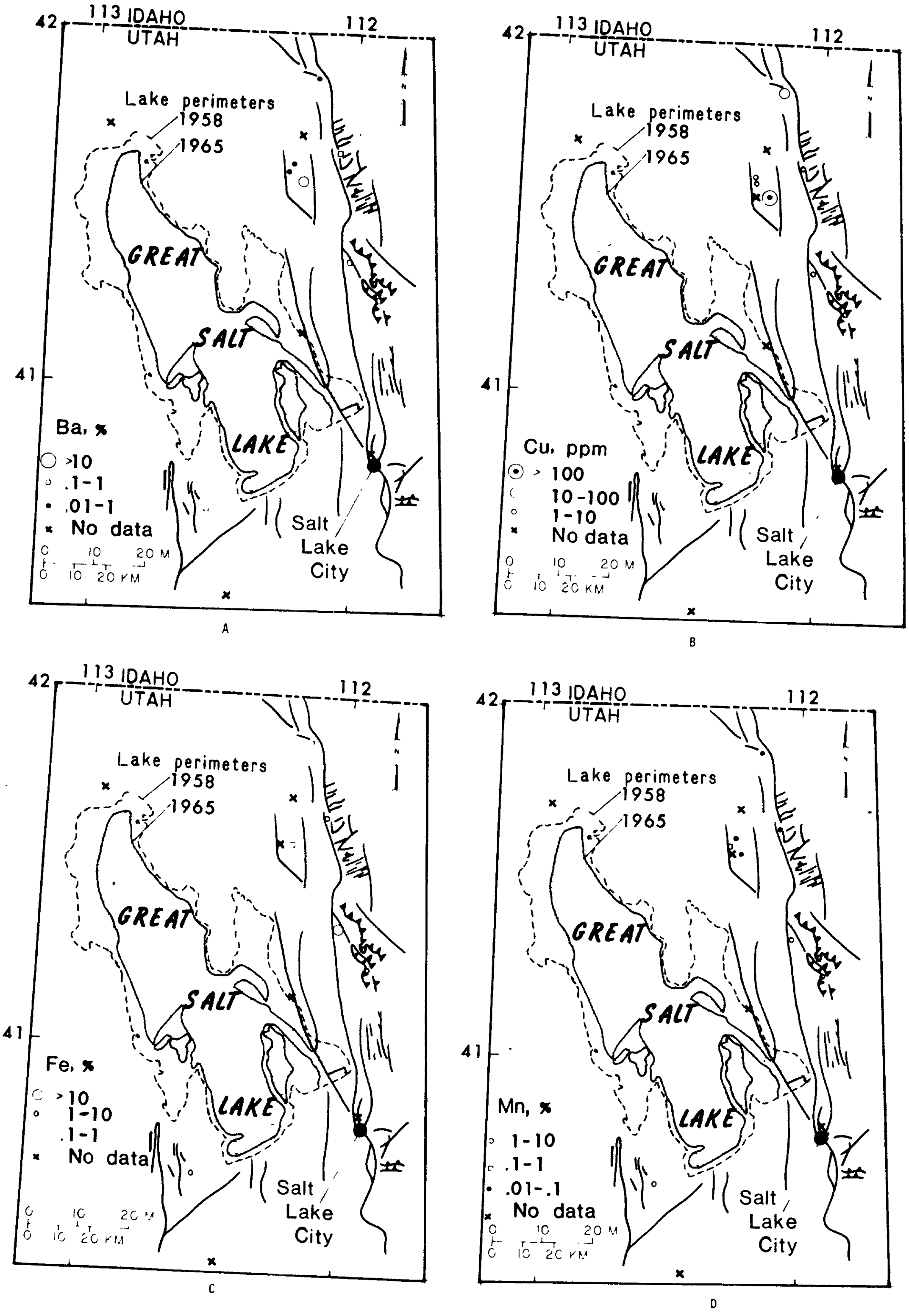

Figure 6.- Ba, Cu, Fe, and Mn contents of spring precipitates.

(Rosholt, 1957, p. 1399)) and by knowing the concentrations of Ra and U at the spring:

	Measured Ra at spring	Calculated Ra in equilibrium with U measured at spring
g/l----------	2.2×10^{-10}	5.1×10^{-13}

$$\text{REF} = \frac{\text{Ra at spring}}{\text{Ra in equilibrium with U at spring}}$$

$$= \frac{2.2 \times 10^{-10} \text{ g Ra/l}}{5.1 \times 10^{-13} \text{ g Ra/l}} = 430$$

Values for REF of springs in the study area are shown in table 3. REF for Crystal Springs is only moderate compared with others in the area. However, Crystal Springs was chosen for the calculation of U because discharge data for the spring as well as other geologic and hydrologic information for that area are available (Bjorklund and McGreevy, 1974). Crystal Springs does show the highest measured Ra, and estimates of reservoir temperature using geothermometry (Fournier and Truesdell, 1973, 1974) indicate that Crystal Springs has a hot-water source that is mixed with a cold-water fraction smaller than others in the area and therefore has a larger contribution from possible late-stage hydrothermal fluids.

The REF in the water depends on the difference in leach between Ra and U when they are removed from the source and transferred to the spring. Differential leaching--based on the differences in response to such geochemical parameters as gas pressures, temperature, oxidation-

Table 3.--REF for springs in study area

[See table 1 for spring names. See text for explanation of REF]

Spring	Measured Ra ($\times 10^{-12}$ g/l)	Measured U ($\times 10^{-6}$ g/l)	Calculated Ra in equilibrium with U ($\times 10^{-13}$ g/l)	REF
St----------	75	0.01	0.03	25000
Li----------	53	1.5	5.1	100
Cr----------	220	1.5	5.1	430
Ud----------	32	.8	2.7	120
Ut----------	66	.04	.14	4700
Pa----------	2.9	2.0	6.8	4.3
Po----------	3.1	1.7	5.8	5.3
Gr----------	5.0	1.4	4.8	10
Mo----------	.26	.5	1.7	1.5
Lo----------	.09	2.7	9.2	.10
Sa----------	.30	1.9	6.5	.46
Ho----------	74	.08	.27	2700
Og----------	21	.28	.95	220

reduction potential, ionic strength, and mineral phases—leads to disequilibrium within the rocks being leached. If the percentage of leach for the two elements is the same, equilibrium in the rocks is maintained and equilibrium amounts are dissolved in the water. Differential leaching in favor of Ra results in an excess of Ra in the water and a corresponding depletion at the source. In time, after several thousand years, continued differential leaching would lead to extreme disequilibrium in the leached part of the rock—the equilibrium Ra would be entirely gone, but the remaining U would be mostly unleached. For Crystal Springs, whose REF is 430, by the time 100 percent of the equilibrium Ra was leached, only 0.23 percent (or 100 percent/430) of the equilibrium U would have been leached. The unleached U would still be present in the rocks and would be producing daughter elements, including Ra, at a certain rate.

Because Crystal Springs is several hundred times enriched in Ra relative to U, we can assume that differential leaching is and has been taking place in the rocks through which water flows to the spring. This differential leaching of Ra may well have led to extreme disequilibrium in the rocks during the several thousand years the flow system is believed to have been in existence. Because Ra in hot springs has been shown to be quite mobile relative to its parents (O'Connell and Kaufmann, 1976, p. 18), we know that the disequilibrium is occurring between Ra and its direct parent, Th^{230}, and that Th^{230} is in relative equilibrium with U. Therefore, we will calculate the U in the source rocks at Crystal by assuming as an approximation that disequilibrium in the rocks is extreme, that no equilibrium Ra is present, and that the only Ra available for transport to the surface is the amount being produced by its parent Th^{230}.

The calculations begin with the known measured values at the spring: (1) the concentration of Ra per liter of water and (2) the volume of water flow per minute. Multiplication of these values gives the rate at which the spring is yielding Ra. Certain assumptions then need to be made. As stated in the previous paragraph, we assume that the amount of Ra available for leach is the Ra being produced each minute. In addition, we assume that 100 percent of the Ra available is leached each minute and is carried to the surface. In other words, we assume that the rate at which Ra appears at the spring is equal to the rate at which Ra is being produced at the source. What needs to be calculated is the amount of U in equilibrium with Th^{230} which produces Ra at that rate. The amount of Th^{230} that is decaying can be calculated by using the half life equation (Howell, 1959, p. 30-37). The amount of U in equilibrium with the Th^{230} can then be determined by using the known equilibrium ratio for those isotopes.

Crystal Springs contains at least 220 µµg/l Ra and is flowing at 6,800 l/min (Mundorff, 1970, p. 14 and 31; Bjorklund and McGreevy, 1974, p. 23); therefore, the spring yields Ra at 1.5×10^{-6} g/min. By assumption, this rate of yield is equal to the rate of Ra production at the source. The production rate of 1.5×10^{-6}g Ra/min is equivalent to a decay rate of 1.5×10^{-6} g Th^{230}/min (mass ratio $Th^{230}:Ra^{226} = 1.02$). The proportion of Th^{230} decaying each minute can be calculated by the half life equation, where

$$x = 1 - e^{-\lambda t},$$

x = proportion of the isotope that has decayed during time t,

1 = 100 percent, or the amount of the isotope at the beginning of decay,

λ = decay constant, or 0.693/half life, and

t = time during which decay has taken place.

For Th^{230}, whose half life is 8.0×10^4 yr, the proportion of any amount of Th^{230} that decays each minute is 1.7×10^{-11}. Since the amount that decays each minute is 1.5×10^{-6} g, then the amount of Th^{230} present, y, is given by

$$(y)\ 1.7 \times 10^{-11}/\text{min.} = 1.5 \times 10^{-6}\ \text{g/min}$$

$$y = \frac{1.5 \times 10^{-6}\ \text{g}}{1.7 \times 10^{-11}}$$

$$= 8.8 \times 10^{4}\ \text{g}$$

Assuming secular equilibrium, where 1 g U is balanced by 1.7×10^{-5} g Th^{230} (Rosholt, 1957, p. 1399), the amount of U required, z, for 8.8×10^4 g Th^{230} is given by

$$\frac{z}{8.8 \times 10^{4}\ \text{g}\ Th^{230}} = \frac{1\ \text{g U}}{1.7 \times 10^{-5}\ \text{g}\ Th^{230}}$$

$$z = \frac{8.8 \times 10^{4}\ (1\ \text{g U})}{1.7 \times 10^{-5}}$$

$$= 5.2 \times 10^9 \text{ g U.}$$

Thus, the amount of U required to maintain the present production of Ra at Crystal Springs is at least 5.2×10^9 g, or 5,200 metric tons.

Estimation of rock volume and possible grades of uranium

Having calculated an amount of U, the next quantity of interest is the amount of rock in which the U occurs. The U occurs in either all or part of the total volume of rock involved in the flow of ground water to Crystal Springs. A maximum volume can be estimated by using hydrologic data and geothermal techniques as applied to a flow model in the region of the spring. Geologic and hydrologic information indicates a flow model as shown in figure 7. Regional ground-water flow is from the Wellsville Mountains in the Wasatch Range westward to the lower Bear River valley and the Great Salt Lake. The ground-water divide is somewhat east of the surface-water drainage divide (Bjorklund and McGreevy, 1974, p. 17). Because the regional flow is westward and Crystal Springs is very near the base of the mountain front, saline water in the basin sediments is not likely to flow eastward to contribute any large quantity of water to the spring. The water at the spring rises along a fault zone (Bjorklund and McGreevy, 1974, p. 23, 41) and is probably composed mostly of deeply circulating meteoric water that may come in contact with a cooling magma chamber or with rocks heated by an intrusive igneous complex. Some magmatic water may enter the system at depth, but lack of hydrogen and oxygen isotope data makes recognition of this contribution unfeasible.

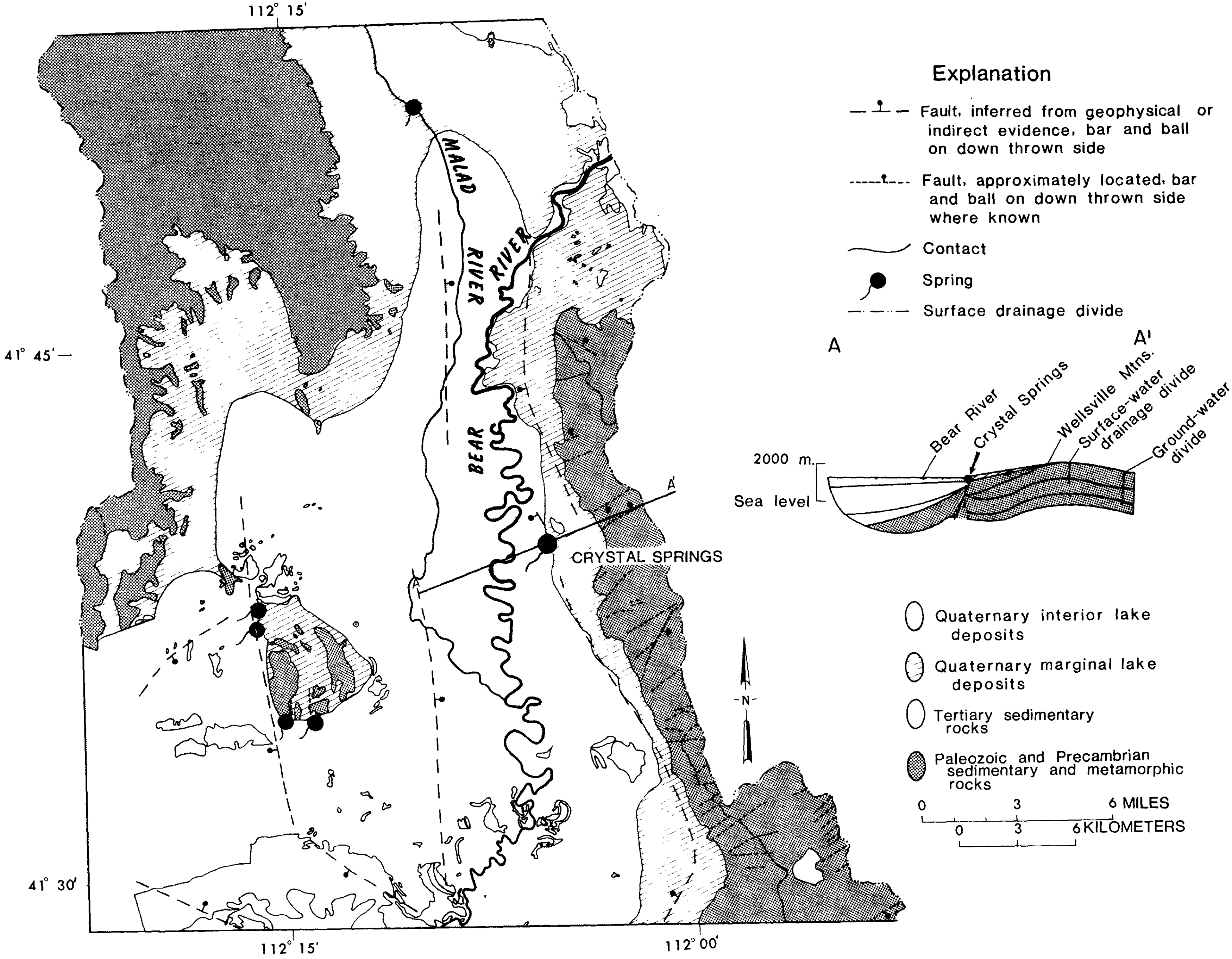

Figure 7.--Geology and water flow pattern in region of Crystal Springs. Modified from Bjorklund and McGreevy (1974).

The total volume of rock involved in the flow to Crystal Springs was determined by estimating the length at 5-10 km, width at 1-3 km, and thickness at 1-2 km (fig. 8). The volume could therefore be from 5 to 60 km^3, or, as an order of magnitude estimate, 10 km^3. The mass of the rock, assuming an average density of 2.8 g/cm^3, is thus 10^{16} g.

The length was measured parallel to the flow direction, or eastward from the spring. The surface-water divide is 5-6 km east of the spring, and the ground-water divide is east of that, perhaps by a few kilometers.

The width was measured perpendicular to the flow direction, along the surface-water divide. Estimated ground-water inflow to the lower Bear River basin at three places along the boundary totals 33 hm^3/yr (Bjorklund and McGreevy, 1974, p. 16-17, 46-47). One of these places is the 20-km-long eastern boundary in the Wellsville Mountains. If one-third of the inflow is along this boundary, then the inflow is about 0.55 $hm^3/yr/km$, or 1.2×10^6 g water/min/km. At this rate, if all the flow at the spring were from ground-water inflow, a 5- to 6-km section of boundary would be needed to supply the 6.8×10^6 g water/min at Crystal. However, some of the water comes from precipitation on the mountains within the basin, and a small amount may even come from magmatic sources. Precipitation on the mountains averages 630 $mm^3/mm^2/yr$ (Bjorklund and McGreevy, 1974, p. 47), or 1.2×10^6 g water/min/km^2. The flow at Crystal Springs can be accounted for by estimating that about one-third of it is ground-water inflow across a 2-km section of boundary and that two-thirds of it is part of the precipitation on a 2-km-wide by 6-km-long area within the basin east of the spring. These

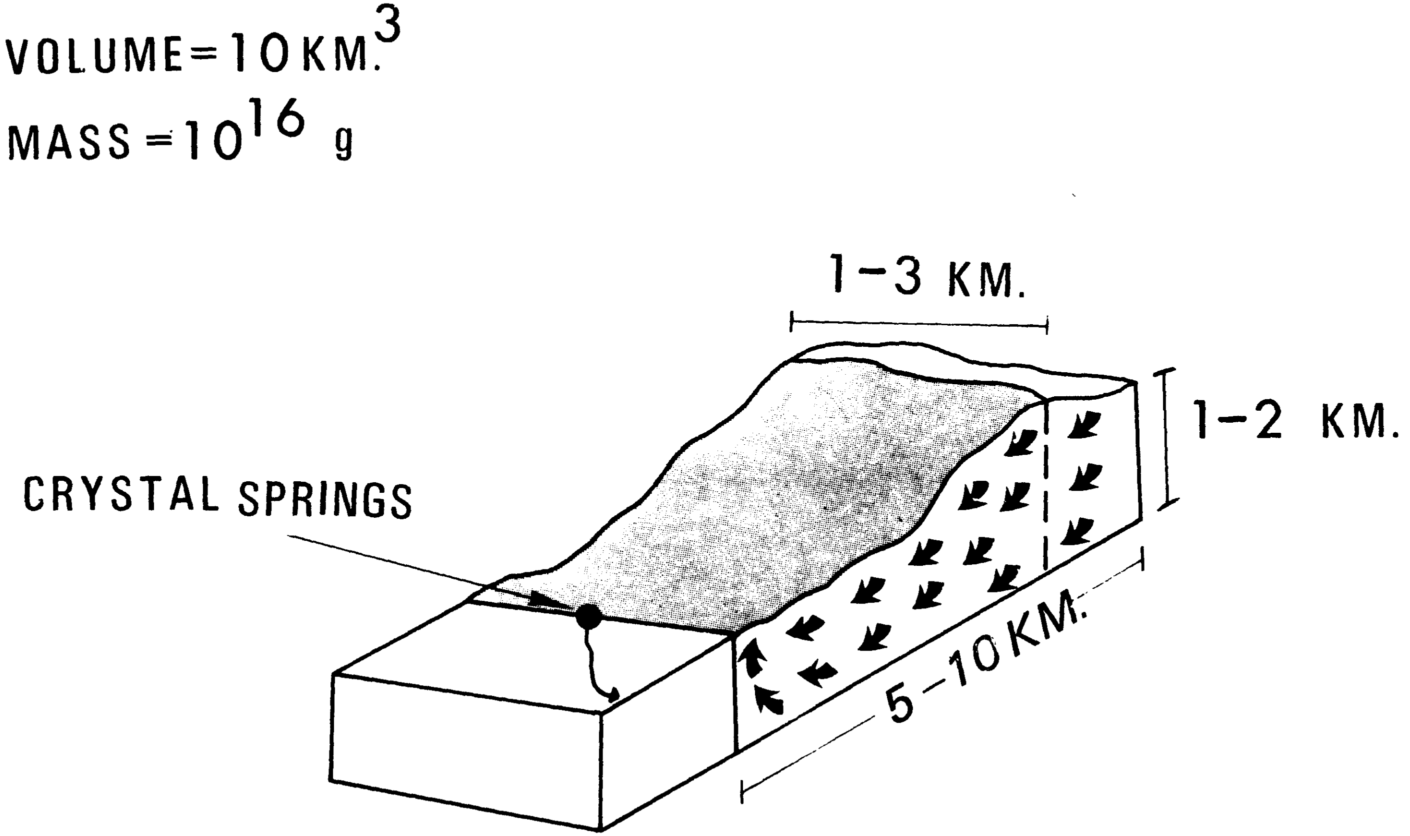

Figure 8.- Estimated total volume of rock involved in flow to Crystal Springs.

calculations indicate that a realistic figure for width is 2 km, or 1-3 km.

The thickness was measured by estimating depth of water circulation on the basis of geothermometry and geothermal gradient. Techniques developed during recent study of active geothermal-hydrothermal systems for energy resource development enable calculation of the maximum temperature attained by circulating thermal water. Application of the Na-K-Ca geothermometer according to the method of Fournier and Truesdell (1973, 1974) indicates that Crystal Springs is a mixed water, composed partly of water that is hotter than the observed surface temperature and partly of colder water that entered the system at relatively shallow depth. Using this model, the estimated maximum temperature for Crystal is 90° C, or about 80° C higher than cold water in the area. The geothermal gradient in the valley areas is 1° C/24 m and is higher in areas of ground-water discharge (Bjorklund and McGreevy, 1974, p. 33), possibly 1° C/15-20 m, somewhat higher than the normal gradient of 1° C/30-55 m (Mundorff, 1970, p. 7; Howell, 1959, p. 47). At this gradient, which may be higher than normal because of an intrusive igneous complex, the water at Crystal Springs must circulate to 1200-1600 m, or 1-2 km.

The calculated U represents U in sites where Ra can be leached. Whether this U is disseminated through the total volume or is concentrated in part of that volume is uncertain. If the calculated 5.2×10^{9} g U were disseminated in 10^{6} g of rock, the U content would be 0.52 ppm. Because this value is even less than the crustal average of 2-4 ppm, it could indicate that the U available for Ra leach is about

12-25 percent of the total U in the rock. Inasmuch as porosity and permeability in the sedimentary-metamorphic terrane of the Wellsville Mountains are controlled mostly by joints and fractures (Bjorklund and McGreevy, 1974, p. 14), water flowing through these openings comes in contact with only a small percentage of the total rock. By assuming that the Ra is derived from U in restricted zones adjacent to fractures and joints, considerably higher potential grades of U in the rock can be calculated. For example, the grade would be 0.52 percent if the 5,200 metric tons of U were concentrated in 1 percent of a fracture system which comprises 1 percent of the volume of rock assumed to be leached by the spring water, or the grade would be 0.06 percent if the U were concentrated in three percent of a fracture system which comprises three percent of the rock.

A few U occurrences are known in the area. Some U was mined from the Precambrian-X Farmington Canyon Complex southeast of Brigham City in the Wasatch Range; the U was in biotite-rich pegmatitic layers in gneisses (Utah Geol. and Mineral. Survey, 1964, p. 131). The U.S. Energy Research and Development Administration (1976, p. 62-64 and pl. 1) estimated the amount of speculative resources in the Farmington Canyon Complex of the Wasatch Range east and southeast of the Crystal Springs area.

Conclusion

In conclusion, we believe that Ra in a spring can be used to estimate the amount of U in a hydrogeologic system from which the Ra is leachable. At Crystal Springs the amount of U was determined to be at least 5,200 metric tons. This U may be in concentrations of economic interest in vein-type or fracture-related deposits at depth along the range-front faults or in the Precambrian and Paleozoic host rocks of the Wasatch Range to the east.

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