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Radioactivity of Geothermal Systems

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ABSTRACT

Radioactivity anomalies associated with hot-spring systems have been recognized and documented for many decades. The most observable radioelements in hot waters are radium-226 and radon-222, both members of the uranium-238 decay series. An examination of hot-spring waters in Nevada indicates the presence of these radioelements, in varying abundances, in spring systems where $CaCO_3$ is the predominant material being deposited. Systems where silica predominates are relatively low in radioactivity. At a hot-spring site in north-central Nevada where $CaCO_3$ predominates, gamma-ray levels from 0.25 to 0.5 milliroentgens per hour were measured over an enclosed warm pool. At other systems where SiO_2 predominates, gamma exposure rates are nearly two orders of magnitude lower.

The emanation of ^{222}Rn from thermalized fault zones is a possible exploration tool in locating a geothermal resource. An alpha-track detector survey within a potential resource area indicates anomalously high Rn associated with hot pools, but a rather featureless Rn pattern in valley alluvium away from the hot springs.

Results of studies combining neutron activation analyses of hot and cold waters in a region, and radiometric analyses of the waters and hot spring deposits, suggest that uranium entering a geothermal system is localized at depth by (1) a reducing environment afforded by H_2S and (2) precipitation of uranyl carbonate. The presence of the U at depth is indicated at the surface by its daughter products, Ra and Rn, in hot-spring waters and deposits.

Along with these geochemical aspects, an understanding of the radioactivity of a geothermal resource is necessary to evaluate the environmental impact of its possible future development.

INTRODUCTION

Radioactive anomalies associated with mineral- and hot-spring systems have been recognized and documented by many scientists. For example, Pöhl-Rüling and Scheminzky (1972) described the radium- and radon-rich environment of Bad Gastein, an Austrian spa celebrated for decades for its healing hot radioactive air, waters, and muds. Earlier, Belin (1959) described the occurrence of radon in New Zealand geothermal regions, and Mazor (1962) related radium and radon in Israeli water sources with oil, gas, and brine reservoirs of the Rift Valley. Since the late 1940's several Japanese scientists, among them Kimura (1949), Kikkawa (1954), and Hitaye (1962), have reported on the association of radioelements and hot- and mineral-spring systems. Scott and Barker (1962) made a comprehensive tabulation of uranium and radium contents of ground waters of the United States. Most recently, Stoker and Kruger (1975, these Proceedings) describe the radon environment of geothermal reservoirs.

Hot-spring areas in northern Nevada, USA, have been visited to evaluate sites for a geothermal energy program (Mirk and Wollenberg, 1974). The radioactivity of the spring systems is being studied (Wollenberg, 1974a), with the expectation that knowledge of the distribution and abundance of their radioelement contents helps define the plumbing systems operating beneath the springs; equally important, an assessment of the environmental impact of potential geothermal resource sites requires an understanding of their radioactive setting.

This paper is comprised of three parts: the first describes radioactivities and radioelements in and around some hot-spring areas; second is a speculative assessment of the mechanism and magnitude of concentration of uranium at depth within some geothermal systems; and finally, the application of a relatively new method of radon detection as a geothermal exploration technique is described. The methods and concepts covered here, though applied to occurrences in the Great Basin of the western United States, may also be relevant to geothermal systems in similar tectonic settings—parts of the earth's crust undergoing extension, characterized by normal faulting.

HOT-SPRING RADIOACTIVITIES

Location

The hot-spring areas examined are shown on the location map (Fig. 1) and are listed by name on Table 1 and 2. At the sites field gamma radioactivity was measured with a portable NaI(Tl) scintillation detector 7.6 cm in diameter and 7.6 cm thick, coupled to a count-rate meter (instrumentation shown in Fig. 2). Field radioactivities were measured over hot pools, sinter (SiO_2-rich), and tufa ($CaCO_3$-rich) deposits, and also away from the spring areas to obtain background values. Figure 3 shows typical measurement conditions at a hot spring in Ruby Valley, Nevada. Samples of spring-deposit tufa, sinter, spring-wall muck, and water were collected at all sites, and on return to the laboratory, were analyzed for uranium-238, thorium-232, their daughter products, and potassium-40 by gamma-ray spectrometry.

Field Measurement Results

Results of field measurement and laboratory gamma-ray spectrometric analyses are shown on Tables 1 and 2. Table

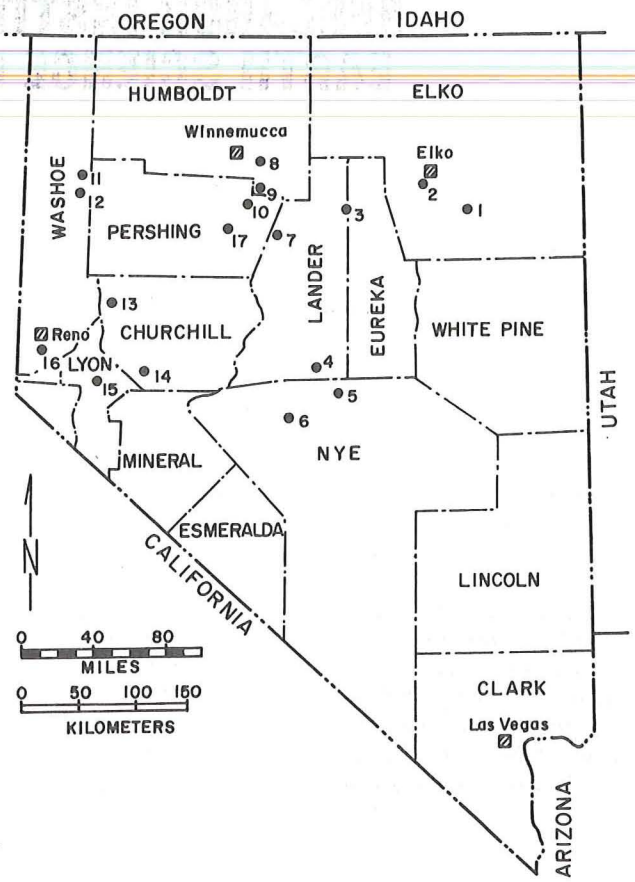


Figure 1. Location map of hot springs visited in Nevada. Numbered springs: (1) Big Sulfur, (2) Elko, (3) Beowawe, (4) Spencer, (5) Diana's Punchbowl, (6) Darrough, (7) Buffalo Valley, (8) Golconda, (9) Pumpernickel, (10) Leach, (11) Fly Ranch, (12) Gerlach, (13) Brady, (14) Lee, (15) Wabuska, (16) Steamboat, (17) Kyle.

Table 1. Field gamma radiometry of spring areas.

Location	Gamma exposure rates (μR/hr) General background	Anomalously high radioactivity	Remarks
Spring systems where $CaCO_3$ is the predominant deposit			
Gerlach	6.25–7.5	60–65	Tufa, high rad. zone
Gerlach	—	20–25	Mixed sinter and tufa
Fly Ranch	6.25–8.75	None apparent	Travertine
Kyle	12.5–25	250–500	Over radioactive pools
Elko	7.5–10	19	Tufa at edge of pool
Buffalo Valley	6.25–7.5	30–38	Tufa mounds
Spencers	5–10	19	Tufa at edge of pools
Diana's Punch-bowl	5–10	16	Springs at base of tufa mound
Wabuska	3.75–6.25	None apparent	Blowing wells
Darroughs	15–20	75	Edge of fenced pool
Darroughs	10–12.5	None apparent	Moderately blowing well
Golconda	12.5–17.5	37.5–175	Pools and interconnecting streams
Pumpernickel	7.5–10	17.5–22.5	Small pool
Pumpernickel	15	17.5	Outflow stream
Spring systems where SiO_2 is the predominant deposit			
Brady	5–7.5	—	Sinter soil
Beowawe	2–2.5	—	Sinter apron
Beowawe	13.8–17.5	—	Andesite, escarpment above blowing wells
Big Sulfur (Ruby V.)	2.5–5	—	Sinter
Leach	5–7.5	—	Sinter
Lee	5–7.5	20–25	Tufa and sinter
Lee	—	10	Edge of pool
Steamboat	2.5–4	—	Main terrace sinter
Steamboat	6.9	—	Altered granitics, west area, blowing well

Figure 2. Field gamma counter. The 3-in. by 3-in. NaI(Tl) scintillation crystal and photomultiplier tube are encased by the steel cylinder, and are connected to the accompanying count-rate meter.

1 summarizes the field radiometric data; radioactivities are expressed in microroentgens per hour (μR/hr), based on calibration of the field instrument (counts/sec to μR/hr) with a radium source of known strength. Immediately apparent is the association of high radioactivities, "anomalies," with $CaCO_3$-rich spring deposits; with one exception, Lee Hot Springs, silica-rich deposits have no anomalies. The greatest radioactivities, 250 to 500 μR/hr, were observed over hot pools (75 to 90°C) at Kyle Hot Springs, while the lowest values, two orders of magnitude lower than at Kyle, were measured over hot and boiling pools and sinter at Beowawe Hot Springs. In no case was there any apparent connection between surface spring temperature and radioactivity. Among the spring systems where $CaCO_3$ predominates, there were no anomalies associated with blowing wells, nor with the fast-flowing spring at Fly Ranch. A strong radioactivity contrast exists at Darroughs Hot Springs where there is no apparent anomaly in the vicinity of a moderately blowing well, while approximately 200 m away 75 μR/hr was observed over a still pool. Thus, radioactive anomalies in the hot-spring areas appear to be associated with low-flowing $CaCO_3$-rich systems. An inverse correlation of radioactivity with flow rate was observed by Vincenz (1959) at a mineral spring in Jamaica.

Where tufa and sinter are both present in a deposit, the calcareous material is highest in radioactivity. This is exemplified at Lee Hot Springs where sinter is the predominant spring deposit material; spotty zones of high radioactivity

Table 2. Laboratory gamma spectrometry of spring deposits.

Location	Description	Th (ppm)	U (ppm)	Equivalent K (%)	^{226}Ra* (pCi/g)	Th/U
Spring systems where $CaCO_3$ is the predominant deposit						
Gerlach	Tufa, high radioactivity zone	13.41	109.25	1.02	39	0.12
	Predominantly Si sinter, some tufa	2.38	33.3	0.41	12	0.07
Fly Ranch	Travertine	2.14	10.99	0.02	4	0.19
Kyle	Calcareous muck from spring walls	11.62	76.32	0.16	27	0.15
	Travertine away from active springs	0.19	4.06	0.09	1.5	0.05
Elko	Tufa	3.12	7.60	0.07	2.7	0.41
Buffalo	Calcareous muck from a small mound	45.89	25.49	0.21	9.2	1.80
Valley	Predominantly tufa, some Si sinter	6.20	65.67	0.35	23.7	0.09
Spencers	Predominantly calcareous mud	10.92	11.54	1.51	4.1	0.95
Golconda	Spring wall tufa	31.20	469.6	—	169	0.07
Pumpernickel	Calcareous muck from small pool	6.33	8.19	0.46	2.9	0.77
Spring systems where SiO_2 is the predominant deposit						
Brady	Mud from hot vent	6.32	2.93	0.41		2.15
Beowawe	Andesite, escarpment above blowing wells	15.99	3.28	3.74		4.88
	Sinter soil, vicinity of hot pools	0.91	0.37	0.40		2.43
Big Sulfur (Ruby Valley)	Sinter	0.18	0.11	0.16		1.60
Leach	Sinter	1.08	0.72	0.35		1.50
Lee	Sinter	4.76	2.49	1.11		1.91
	Tufa and sinter	3.71	11.67	0.51		0.31
Steamboat	Sinter, main terrace	0.30	1.42	0.13		0.21
	Sinter and altered granitics, west area	8.10	4.90	1.13		1.65

*Calculated from activities ratio, $^{226}Ra/^{238}U = 2.78 \times 10^6$.

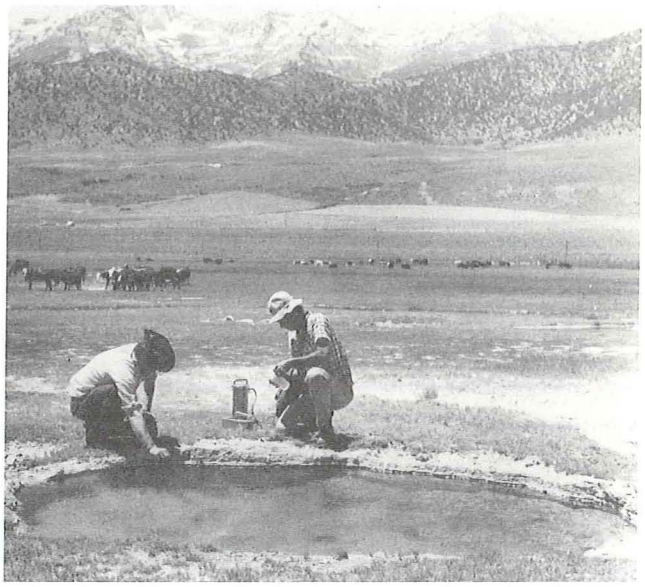


Figure 3. Field gamma radioactivity and water-temperature measurements at Big Sulfur Hot Springs, Ruby Valley, Nevada.

were observed over intermixed patches of tufa, while neighboring sinter was comparatively low. Similarly, tufa is highest in radioactivity at Gerlach Hot Springs where siliceous and calcareous zones intermingle.

At Buffalo Valley and Kyle Hot Springs $CaCO_3$-rich sites, sharp field-radiometric anomalies were detected downwind from pools, indicating the emanation of ^{222}Rn from the waters and spring walls.

Laboratory Measurement Results

Spring deposits. Table 2 summarizes laboratory gamma-spectrometric analyses of spring-deposit materials. As with the field data, the high radioactivities, attributable primarily to equivalent U, are associated with the calcareous hot-spring deposits. Siliceous deposits are comparatively low in U and Th, and most have Th/U ratios similar to those of ordinary siliceous rocks. Exceptions are the mixed tufa and sinter soil at Lee Hot Springs, where the tufa introduces relatively high equivalent U, and at the low-radioactivity sinter terrace at Steamboat Hot Springs.

For guidance in the following discussion the uranium decay series is shown in Figure 4. The uranium values in Table 2 are listed as equivalent because they are based on the gamma-ray peaks of ^{214}Bi, one of the radioactive decay products of ^{226}Ra. Radium-226, in some chemical environments, may be completely separated from its parent ^{238}U, transported in bicarbonate-rich waters, and deposited with $CaCO_3$ on spring walls in the upper portions of a spring system (Tanner, 1964). Therefore, the high equivalent U in samples of calcareous deposits actually indicates ^{226}Ra anomalies. Uranium-238 or its decay products higher in atomic mass number than ^{226}Ra are missing. This was disclosed by examing high-resolution gamma-ray spectra of the calcareous samples, counted on a Ge(Li) detector system. Figure 5 displays superimposed gamma-ray spectra in the x-ray energy region of a ^{226}Ra source, calcareous muck from Kyle Hot Springs, and an equilibrium ^{238}U standard. The muck and ^{226}Ra source spectra match peak for peak. The U-standard spectrum shows the characteristic Bi and Pb x-ray peaks, as well as peaks from precursors to Ra in the U-decay series. Corroborative evidence for radon anomalies in the calcareous material is furnished by comparison of the intensities of peaks at 186 and 352 keV (not shown on Fig. 5) in the equilibrium and Ra spectra. In the U spectrum 62% of the 186-keV peak is from ^{226}Ra, 38% from ^{235}U, while all of the 352-keV peak is from ^{214}Po, a Ra daughter; the ratio of counts in the 352-keV peak to counts in the 186-keV peak is approximately 2:1. In samples of Ra-rich spring deposits the corresponding peak ratios are approximately 3:1, indicating the absence of the ^{235}U component in the 186-keV peak.

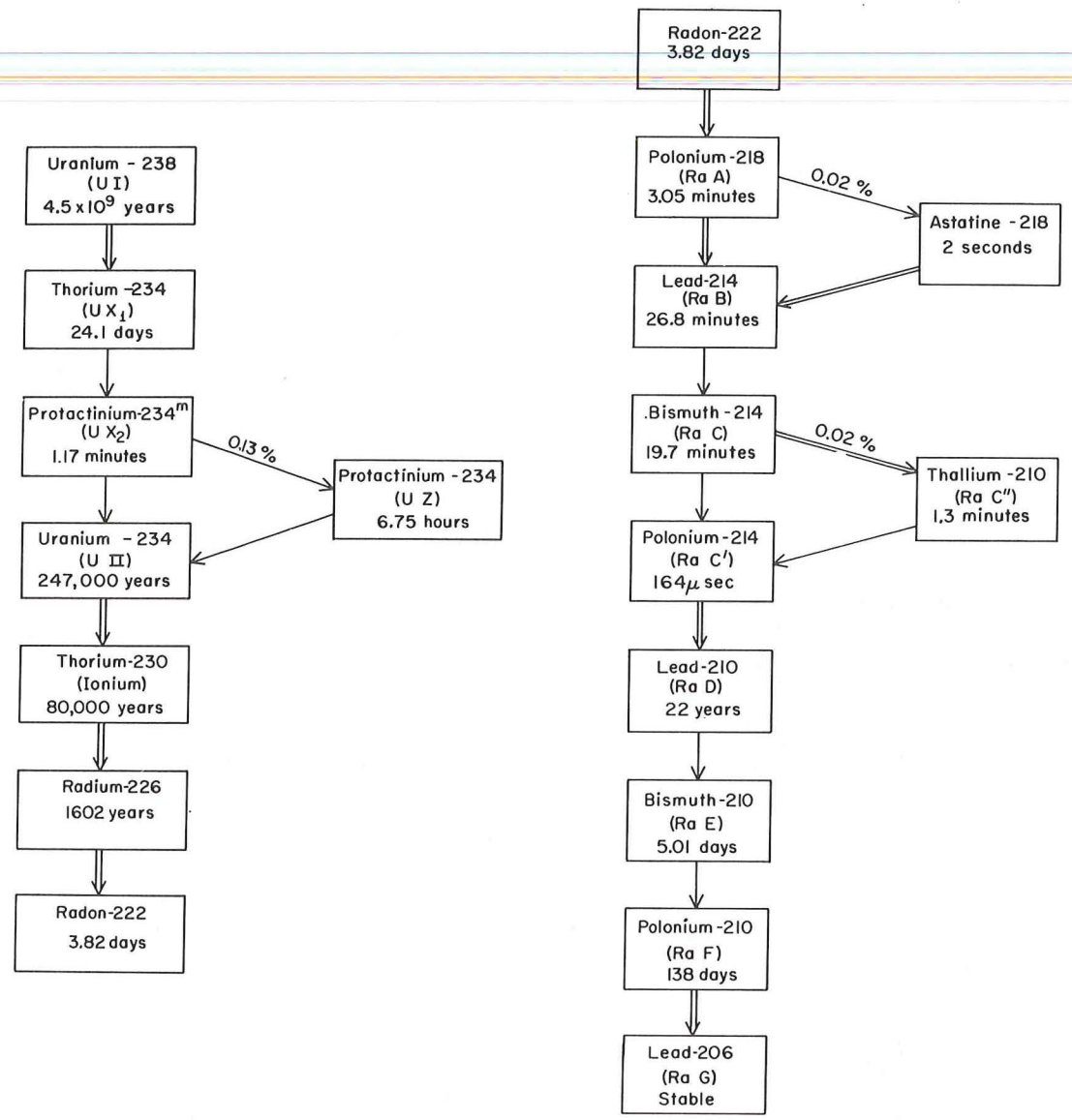


Figure 4. The uranium-238 decay series, indicating half-lives.

Waters. Samples of water, approximately 550 ml, were collected from all of the springs for subsequent laboratory gamma-ray spectrometry. Radon-222 was indicated by the presence of the 1.76-MeV peak of ^{214}Bi in the gamma spectra of seven of the water samples. Several days elapsed between collection and laboratory analyses of the samples. Therefore, it is expected that in some of the samples ^{222}Rn activity (a 3.8-day half-life) had decayed below detectability. Repeated gamma counting of the samples from Buffalo Valley, Kyle, and Gerlach Hot Springs showed that the ^{214}Bi activity decayed with the Rn half-life, indicating that there was little or no ^{226}Ra in these waters. Otherwise, Ra would have resupplied Rn, eventually achieving radioactive equilibrium between these isotopes. The ^{214}Bi activities of the measurable water samples and their calculated ^{222}Rn contents are listed in Table 3. There is no apparent correlation between the radioactivities of the waters and those of the calcareous hot-spring deposits. The comparatively high radioactivities of the waters from Pumpernickel and Lee Hot Springs, compared with the relatively low activities of corresponding spring deposit material, suggest that these waters may contain radon from sources other than the radium on near-surface spring walls. Planned sampling of hot-spring waters shall include on-site radon analyses and chemical separation of radium, which, coupled with subsequent laboratory analyses, should determine the component of radon from radium in the waters and the component emanating from radium deposited near the surface.

GEOTHERMAL CONCENTRATION OF URANIUM

Uranium contents of hot- and cold-spring waters, and springflow volumes can be combined to furnish an estimate of the amount of uranium which may be concentrating at depth within a geothermal system. At this stage of our studies, such estimates must be treated as speculative. Speculations are based on several assumptions, not the least tenuous of which is the model of a geothermal system, illustrated in Figure 6. In this model it is assumed that meteoric waters enter a geothermal system after transversing country-rock aquifers of varying intrinsic U contents. The geothermal system is provided by convection cells within

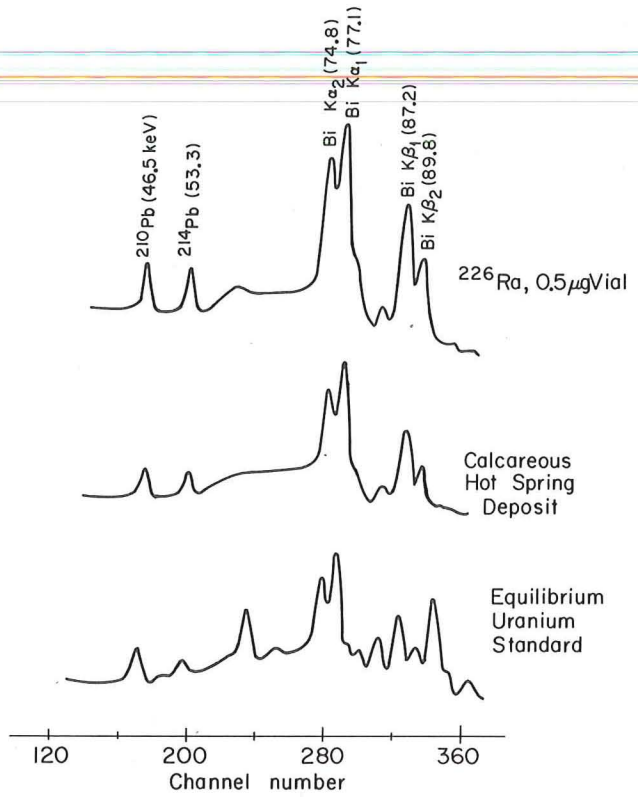


Figure 5. Gamma-ray spectra in the energy region 40 to 100 keV. The spectra were taken on a high-resolution system, utilizing a 10-cm^3 Ge(Li) detector.

Table 3. Radioactivity and radon content of hot-spring waters.

Location	Net radioactivity in 1.76 MeV peak of ^{214}Bi (counts min^{-1} g^{-1})*	Calculated ^{222}Rn content (pCi l^{-1})
Gerlach	0.0117	258
Kyle	0.0179	587
Buffalo Valley	0.0034	73
Golconda	0.0070	207
Pumpernickel:		
Small pool	0.0362	1299
Outflow	0.0162	543
Lee	0.0166	556

*Corrected for 3.8-day half life of ^{222}Rn.

a permeable fault zone, penetrating deeply (3 to 5 km) into a region where geothermal gradients may range from 30 to over 50°C km^{-1}. In northern Nevada, uranium contents of bedrock terranes vary from 1 to a few ppm in Tertiary basaltic and Mesozoic clastic and carbonate rocks, up to 10 to 20 ppm in Tertiary acidic volcanic rocks and Mesozoic plutons. These variations in uranium are similar to variations in many other terranes throughout the world.

Chemical contents of cold springs in these bedrock terranes may be indicative of chemistries of ground waters percolating into geothermal fault zone systems. Such data are described in another paper in these Proceedings (Bowman et al., 1975). Hot- and cold-spring uranium contents (by neutron activation analysis) are summarized in Table 4. Inspection of Table 4 indicates that uranium contents of cold spring waters are appreciable (1 to over 3 ppb), while hot springs have very little uranium. But, as has been pointed out in earlier sections, spring systems depositing $CaCO_3$, such as Kyle and Buffalo Valley hot springs, have appreciable contents of uranium daughters in waters and deposits. At these locations, one can postulate that uranium may be concentrating at depth within the geothermal systems. (It may also be concentrating at depth in systems dominated by SiO_2, but its presence is not obvious because U-daughters are not abundant in these springs.) The mechanism of concentration is twofold. Uranium, as the uranyl (U^{+6}) ion, is fairly mobile in an oxidizing environment. Uranyl carbonate may be transported in ground water into a geothermal system, where it is reduced to U^{+4} in a reducing environment provided in large part by H_2S, a ubiquitous component of hot springs. Uranyl carbonate, as in the case with most carbonates, has retrograde solubility; it precipitates at high temperature (Blake et al., 1956). Thus, the presence of a high-temperature, reducing environment favors concentration of U, as it is reduced from U^{+6} to U^{+4}, and the carbonate is precipitated.

The amounts of uranium concentrating at depth in the systems at Kyle, Leach, and Buffalo Valley Hot Springs are estimated on Table 4. Estimates are based on flow rates of the hot springs (Olmsted et al., 1975), U contents of hot- and cold-spring waters, and the assumption that U contents of cold spring waters represent U contents of ground waters entering the geothermal systems. These estimates suggest that uranium concentrations of the order of several tens of kilograms may have formed over several thousand years. Such time spans are not unreasonable, considering the ephemeral nature of hot springs in this region of tectonic instability, the Basin and Range geomorphic province.

RADON ALPHA-TRACK SURVEY

The registration of alpha particles in plastics has been applied to the search for uranium in recent years. The basic track etch concept (Fleischer et al., 1972) was modified and patented by scientists of the Terradex Corporation (Alter et al., 1972) and the General Electric Vallecitos Laboratory to detect alpha particles from the decay of radon-222, a gaseous daughter product of uranium-238. Inverted plastic

Table 4. Estimation of uranium deposition rates in three hot-spring systems.

Location	Mean U content (ppb) Cold waters	Hot waters	Difference	Flow rate (ml yr^{-1})*	U deposition (g yr^{-1})
Buffalo Valley	1.3	~ 0.1	1.2	2.1×10^{11}	2.52×10^{2}
Kyle	3.07	~ 0.5	2.6	1.05×10^{10}	2.73×10^{1}
Leach	1.52	~ 0.2	1.3	3.5×10^{11}	4.52×10^{2}

From Olmsted et al. (1975) for Buffalo Valley and Leach; Mariner et al. (1975) for Buffalo Valley and Leach; Mariner et al. (1974) for Kyle.

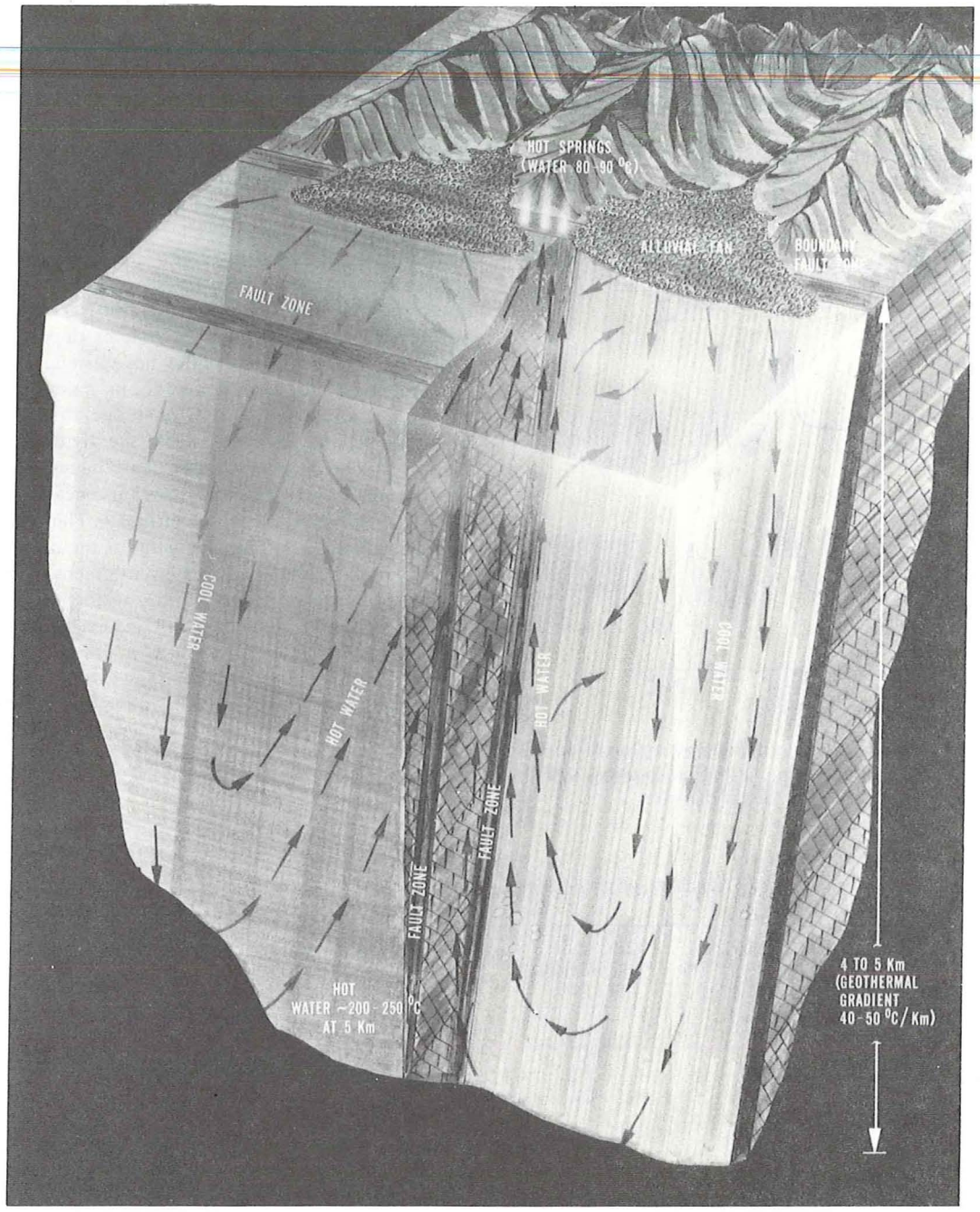


Figure 6. Schematic cutaway diagram of a geothermal system within a permeable fault zone. Meteoric water enters the fault zone where it intersects near-surface aquifers. Some of the water percolates downward to regions where temperatures reach 150 to 200°C, is heated, and rises on the upward limb of a convection cell. Hot springs occur where the cell intersects the surface.

cups with a specially treated dielectric alpha-track detector attached inside are placed, each in an approximately 0.5-m-deep hole, in arrays of varying extent. The walls of the cup are thick enough to exclude alpha particles from radon in the air surrounding the cup; the only contribution is from radon emanating from soil directly beneath the mouth of the inverted cup. After exposure of several weeks, the cups are retrieved and the detectors are removed and etched, revealing track densities proportional to the emanating radon flux. Significant uranium ore bodies, not detected by more traditional gamma-ray surveys, have been discovered by this method (Gingrich, 1974). It has been shown that radon travels through several tens of meters of overburden, which otherwise conceals an ore deposit by shielding its gamma radiation.

Earlier in this paper the association was described of radon emanations with some hot-spring systems, especially those where calcium carbonate predominates. It was considered that an array of radon alpha-track detectors near and away from a radioactive spring system might indicate fault zones along which warm, radon- and radium-enriched waters were migrating. Israël and Björnsson (1967) described high concentrations of soil-gas radon associated with such fault zones in the vicinities of Bad Nauheim and Aachen.

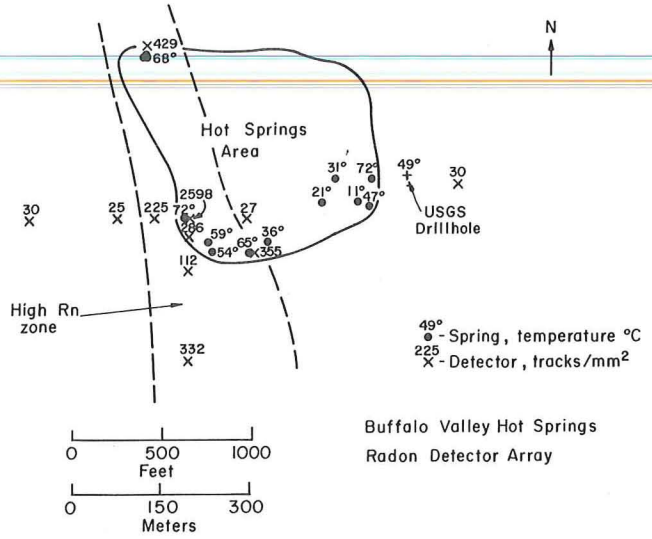


Figure 7. Sketch map of Buffalo Valley Hot Springs area, showing locations of some of the warm pools, temperatures, and normalized track densities.

Procedures

For the Nevada studies, a good test site was afforded by hot springs in Buffalo Valley in the north-central part of the state (site No. 7 on location map, Fig. 1). Because of the sharply varying gamma-ray fields measured at the springs, a set of alpha-track detectors was installed in their immediate area. (A map of the hot springs area, showing detector locations, comprises Fig. 7.) Also, an array of detectors, covering a much larger area, was installed in the valley surrounding the hot springs; detector locations and track density contours are shown in Figure 8. The track-etch detectors, mounted in plastic cups, were generously provided and processed by the Terradex Corporation (a track-etch service corporation affiliate of General Electric).

Uranium and Radon

Comparison of track densities and uranium content of surficial material provides a qualitative indicator of the effect, if any, of soil uranium on the observed track densities. Therefore, to determine the uranium content of the soil directly beneath and surrounding the cups, samples of soil from the cup holes were collected and later analyzed for natural radioelement contents by gamma spectrometry at Lawrence Berkeley Laboratory. There is no apparent correlation between near-surface uranium content and track density (Wollenberg, 1974b). Frequency distributions of U and track densities are shown as histograms in Figure 9. The ranges of U content are not nearly so broad as the range in track densities.

Radon Emanation Near the Hot Springs

Inspection of the map (Fig. 7) shows that the small pools and mounds at Buffalo Valley Hot Springs, from which radon emanates, are associated with high track densities (several hundred to several thousand tracks/mm^2) in detectors placed nearby. However, at some locations only a few tens of meters away from the mounds and pools, well within the springs area, track densities are "normal" (tens of tracks/mm^2), while at other locations, roughly equidistant from the radioactive pools, densities are appreciably greater than normal. Therefore, radon emanations vary sharply within the springs area, though a general north-south-trending "high" is indicated on Figure 7.

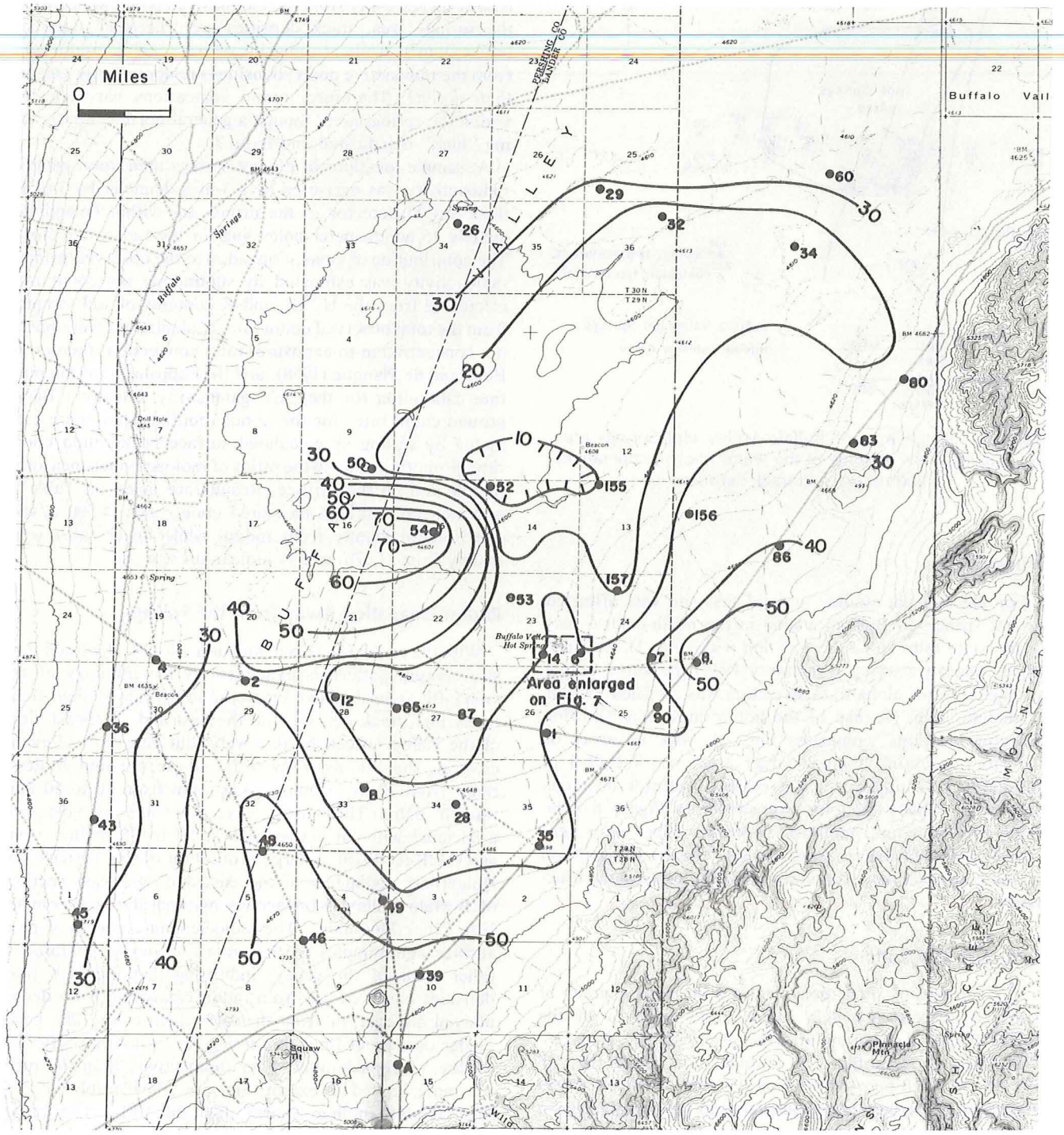
At sample locations in the hot-springs area, total gamma radioactivity was measured by a 3-inch-diameter by 3-inch-thick NaI(Tl) detector, on the surface and within the approximately 15 cm-diameter holes dug for the radon detectors. The contribution of emanating radon to the observed gamma radioactivity was estimated by subtracting the count rate calculated from the U, Th, and K contents of soil samples from the total observed count rate. (Calculations were based on concentration-to-exposure rate conversion factors in Beck and de Planque (1968), and the exposure rate-to-count rate calibration for the field gamma-ray detector.) Background count rates for the in-hole configuration were estimated by scaling up calculated surface background count rates proportionately to the ratios of radioactivities measured in-hole and on the surface. Results are listed on Table 5, and indicate that high measured count rates (>500 c/sec) were predominantly from radon, while lower rates were mainly from U, Th, and K in near-surface soil.

Radon Emanation Away from the Springs

With the exception of one location, No. 54, the track-density contour pattern is explained by the lithology of the valley-fill and sub-alluvial material in Buffalo Valley. Relatively high track densities on the east and southeast sides of the valley reflect the relatively thin veneer of alluvium covering rhyolitic ash-flow tuffs, whose uranium contents range from 10 to 15 ppm and thorium from 30 to 50 ppm (unpub. data). These tuffs were deposited by volcanism associated with an active caldera 20 to 25 million years ago (McKee, 1970). A large proportion of the Tertiary and Quaternary sediments in the east and southeast sections of Buffalo Valley is tuffaceous material derived from the Fish Creek Mountains. The radioelement contents of near-surface soil samples in this area are similar to those in other areas of the valley, indicating that the high track densities observed are from radon emanating from deeper alluvial material, or from the tuffs themselves. The basalt cinder cones and flows bordering the east side of Buffalo Valley, of considerably lower radioactivity than the tuffs, are more limited in extent, and are considerably younger (age about 3 million years) than the tuffs. The basalt, therefore, has not contributed as much material to the deeper alluvium. Relatively low track densities in the rest of the area covered reflect the deep alluvial material, where debris predominates from Paleozoic and Mesozoic sedimentary terranes in the Tobin Range and northern Fish Creek Mountains.

CONCLUSIONS

Radium, and therefore, high radioactivity, preferentially associates with $CaCO_3$ in hot-spring deposits. Where sinter and tufa are mixed in a deposit, the calcareous material has the highest radioactivity. Low-flowing, $CaCO_3$-dominated spring systems appear to be the most radioactive. Some of the ^{222}Rn measured in hot-spring waters is derived directly



Base Map: USGS Buffalo Springs (1962) and McCoy (1961) quadrangles

Figure 8. Contours of radon alpha-track density (in tracks/mm, normalized to a 30-day exposure) in Buffalo Valley. Dotted numbers: locations.

from ^{226}Ra deposited on the spring walls, some from U and Ra at depth.

Relatively high uranium contents of cold-spring waters, compared to low contents in surface waters of hot springs, within a hydrologic area, suggest that uranium may be concentrated at depth within geothermal systems. The most likely mechanisms are reduction of U^{+6} to U^{+4} as meteoric water enters the system, and the retrograde solubility of uranium carbonate.

Radon alpha-track detectors, presently used successfully to delineate concealed uranium deposits, are also sensitive to radon emanated from radioactive geothermal systems.

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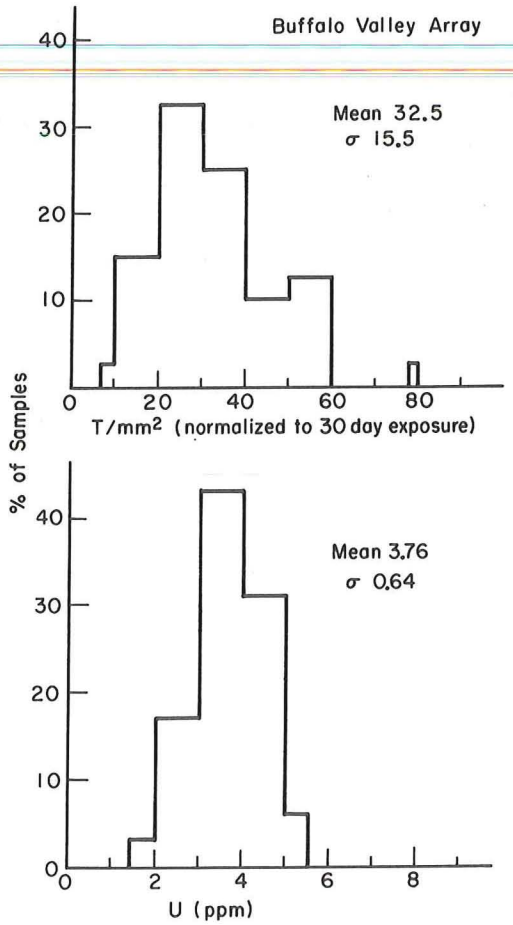

Figure 9. Frequency distribution of track densities normalized to a 30-day exposure (a), and (b), uranium contents of soils from track detector holes in Buffalo Valley.

spectrometry and was very helpful in its interpretation. I thank Harry Bowman, Alvin Hebert, and Frank Asaro of LBL for stimulating discussions on probable mechanisms of uranium concentration, and Daniel Lovett of General Electric and H. W. Alter and James Gingrich of Terradex Corporation for preparation and processing of alpha-track detectors. Most of the track detectors were emplaced and retrieved, and soil samples obtained, by R. Solbau of the LBL Geothermal Group, to whom the author is indebted.

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Table 5. Observed, background, and net gamma radioactivities from ^{222}Rn in counts per second, in Buffalo Hot Springs area.

	Observed		Background from U,Th,K in soil		Net, from Rn	
Tracks/mm²	Surface	In-hole	Surface	In-hole	Surface	In-hole
2598	2000	3500	210	368	1890	3132
—	750	1700	240	544	510	1156
27	400	575	335	481	65	94
355	1200	2100	242	423	958	1677
429	1200	2900	186	450	1014	2450
30	500	750	417	625	83	125
56	575	750	490	639	85	111
112	320	430	283	380	37	50
332	420	550	300	392	120	158
225	300	300	137	137	163	163

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