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Radioactive Mineral Springs in Delta County, Colorado

By

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Contents

Illustrations

Tables

RADIOACTIVE MINERAL SPRINGS IN DELTA COUNTY, COLORADO[1/]

By Robert A. Cadigan, J. Karen Felmlee, and John N. Rosholt

Abstract

The system of springs in Delta County, Colo., contains geochemical clues to the nature and location of buried uranium-mineralized rock. The springs, which occur along the Gunnison River and a principal tributary between Delta and Paonia, are regarded as evidence of a still-functioning hydrothermal system. Associated with the springs are hydrogen sulfide and sulfur dioxide gas seeps, carbon dioxide gas-powered geysers, thick travertine deposits including radioactive travertine, and a flowing warm-water (41°C) radioactive well.

Geochemical study of the springs is based on surface observations, on-site water-property measurements, and sampling of water, travertine, soft precipitates, and mud. The spring deposits are mostly carbonates, sulfates, sulfides, and chlorides that locally contain notable amounts of some elements, such as arsenic, barium, lithium, and radium. Samples from five localities have somewhat different trace element assemblages even though they are related to the same hydrothermal system. All the spring waters but one are dominated by sodium chloride or sodium bicarbonate. The exception is an acid sulfate water with a pH of 2.9, which contains high concentrations of aluminum and iron.

Most of the detectable radioactivity is due to the presence of radium-226, a uranium daughter product, but at least one spring precipitate contains abundant radium-228, a thorium daughter product. The 5:1 ratio of radium-228 to radium-226 suggests the proximity of a vein-type deposit as a source for the radium. The proposed locus of a thorium-uranium mineral deposit is believed to lie in the vicinity of Paonia, Colo. Exact direction and depth are not determinable from data now available.

[1/] Based on talk given at the U.S. Geological Survey Uranium and Thorium Research and Resource Conference held December 8-10, 1975, at Golden, Colorado.

Introduction

As part of the effort to evaluate the potential uranium resources of the United States, the U.S. Geological Survey has begun to study the sources of a group of conspicuously radioactive sedimentary rocks which occur at the surface of the Earth. These rocks are the radioactive travertines and associated mineral precipitates, and their immediate sources are the so-called mineral springs.

Mineral springs, both hot and cold, have been valued for their therapeutic effects for thousands of years. Many towns in Europe and the United States began as resorts connected with springs or baths and even named themselves after these reputed health-giving waters. During the 18th and 19th centuries, it became fashionable to spend a vacation at a "spa," "bad," or "bath" at a spring resort. The result of this economically important fad was that even before geologists became interested, nearly all mineral springs in the United States had been found, recorded, and examined for general composition, taste, and health-giving properties.

Among the more obscure mineral springs valued locally for their medicinal properties are those near Austin in Delta County, Colorado (fig. 1). Investigation of the Austin springs by the authors led to a study of the area from Austin eastward along the Gunnison River and the North Fork of the Gunnison River. The main product of this study was the recognition of an old, but still functioning, hydrothermal system with surface manifestations from Austin to Paonia; many cold mineral springs and seeps along the river between Austin and Hotchkiss, two cold carbon dioxide geysers, sulfurous gas seeps, extensive travertine deposits including radioactive travertine, and a 500-metre-deep flowing well of warm CO_2-gas-charged radioactive water.

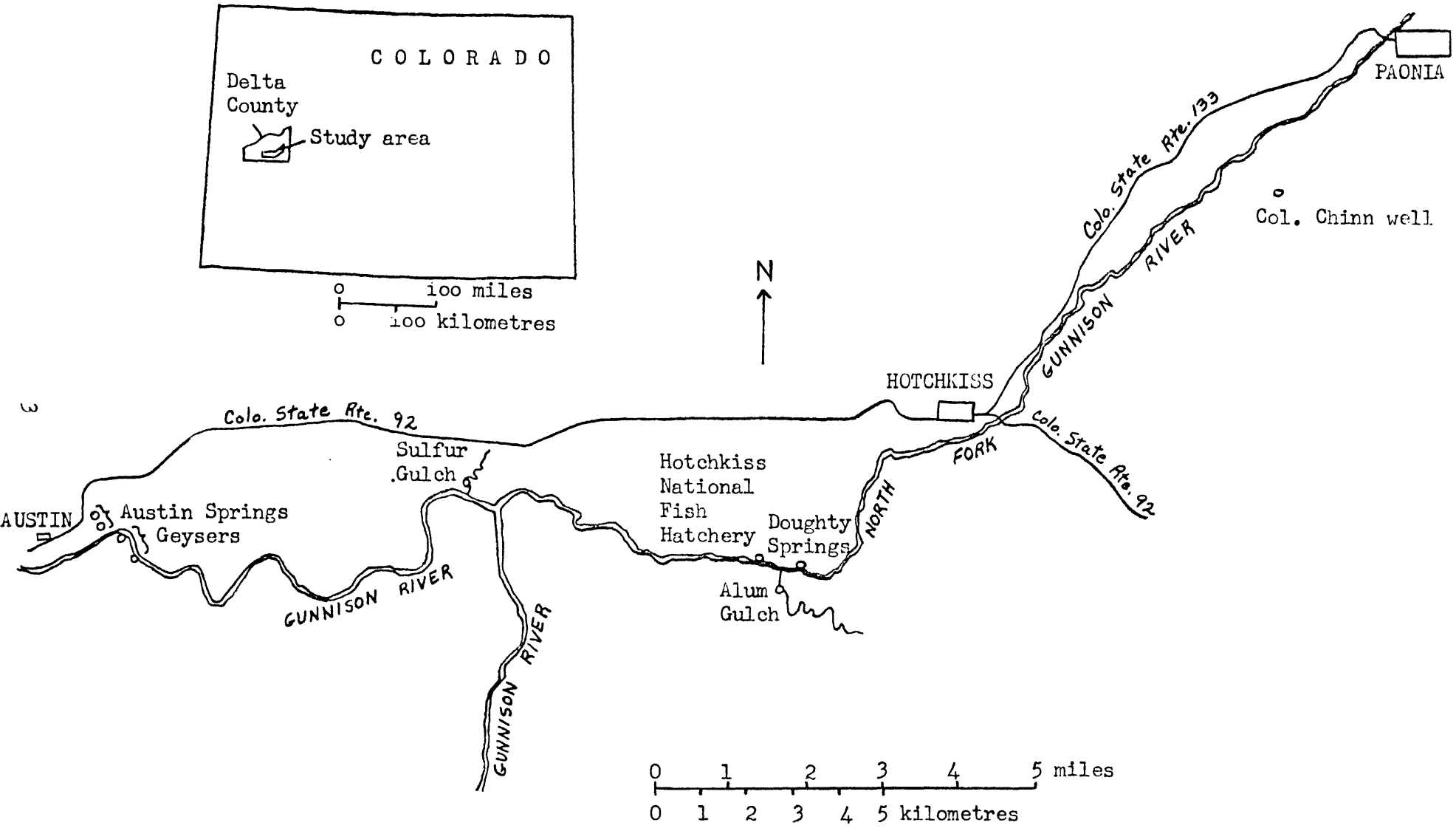


Figure 1. Index and locality map of study area.

The investigation was begun when two analyses of water from springs in the Austin area by P. R. Barnett and E. C. Mallory (written commun., 1972) were brought to our attention by A. E. Bush. R. P. Fischer recommended a visit to Sulfur Gulch to check the observations of M. G. Dings (1949). A review of the literature on mineral springs in Colorado revealed that W. P. Headden (1905 and 1909) had described springs near Austin and at Doughty Springs and had reported the presence of the Col. Chinn well near Paonia.

General geology

The geologic setting of this hydrothermal system is typical of the Colorado Plateau. The surface is composed of flat-lying Mancos Shale of Cretaceous age overlain in places by Quaternary terrace gravels derived partly from sources to the east and partly from Grand Mesa to the north (figs. 2 and 3). Underlying the Mancos, the Dakota Sandstone and Burro Canyon Formation of Cretaceous age and the Morrison Formation of Jurassic age are exposed in canyon walls along the Gunnison and its tributaries. The Burro Canyon Formation is present at Austin but thins eastward and pinches out in the vicinity of Sulfur Gulch. South of the study area, other Jurassic sedimentary rocks--Junction Creek Sandstone, Wanakah Formation, and Entrada Sandstone--are exposed overlying Precambrian metamorphic rocks in the Gunnison River canyon. At most localities, the mineral springs emerge from the basal contact of the Dakota Sandstone or from parting planes in the Dakota Sandstone or in basal sandstones of the Mancos Shale, but at Austin a major monoclinal fold produces a faulted and fractured zone in basal Cretaceous rocks from which the springs and seeps emerge (fig. 4).

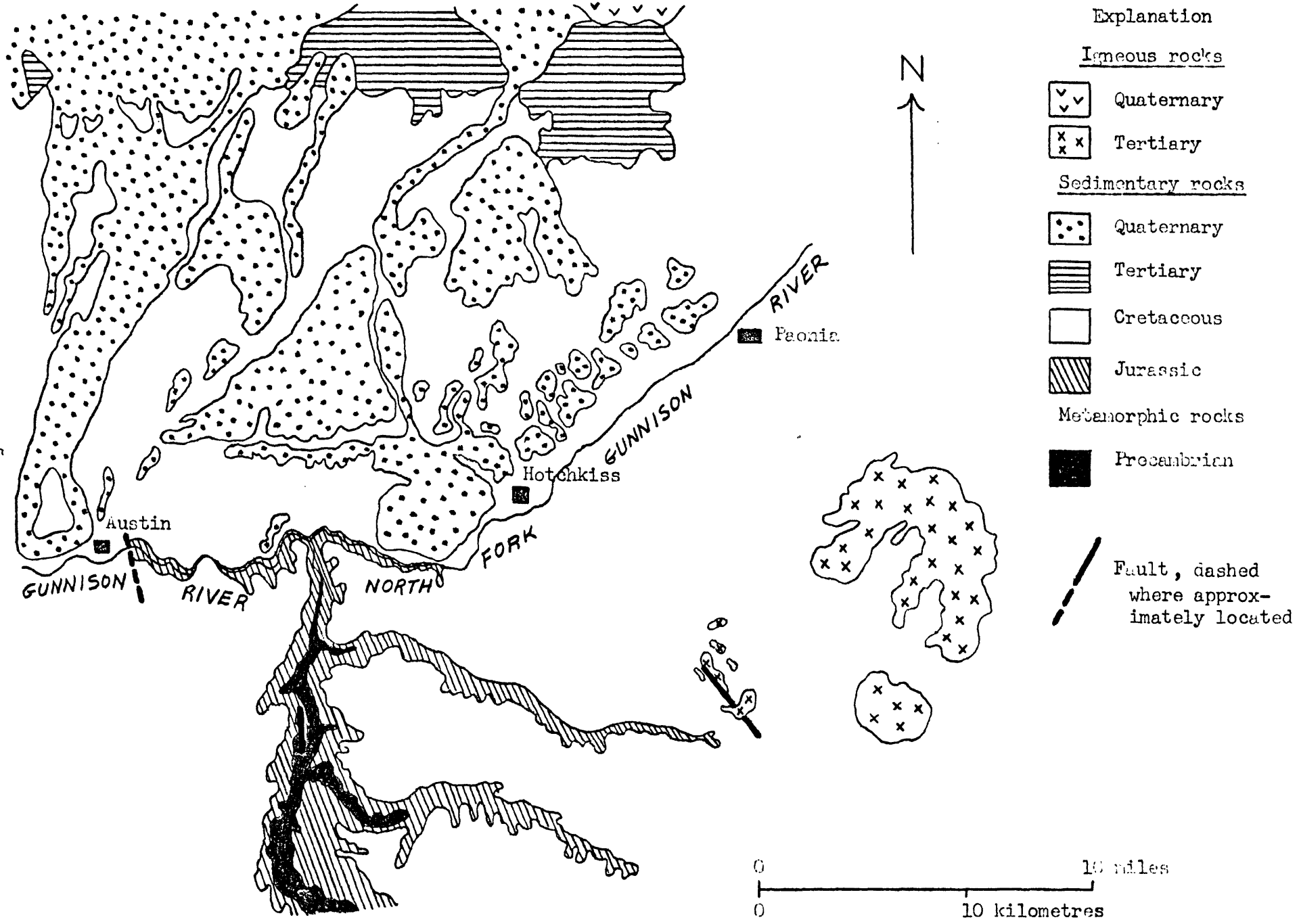


Figure 2. Geologic map of south-central Delta County. (Modified from Hail, 1972a, b.)

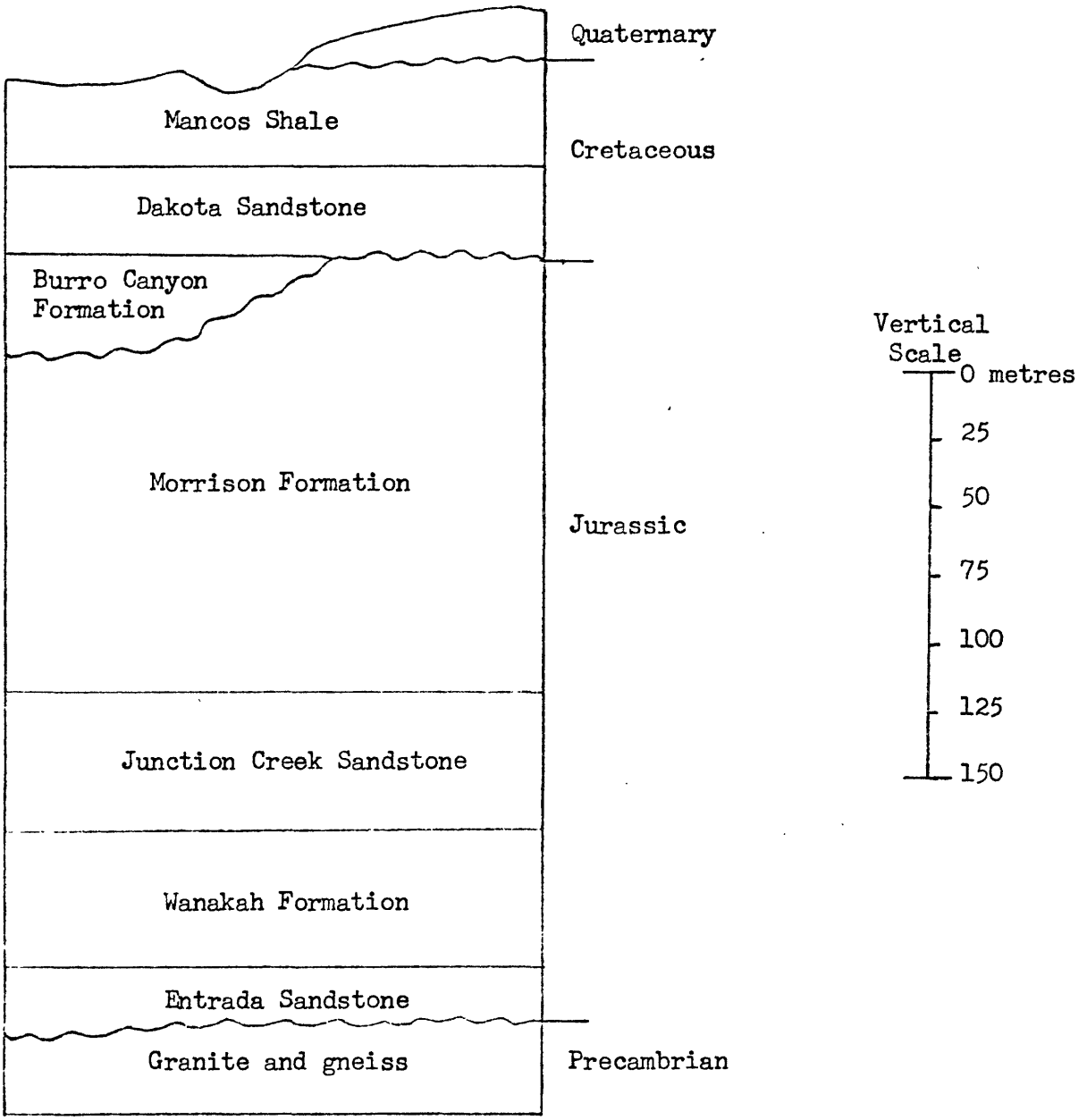


Figure 3.--Diagrammatic stratigraphic column for study area. (Modified from Mullens, 1950.)

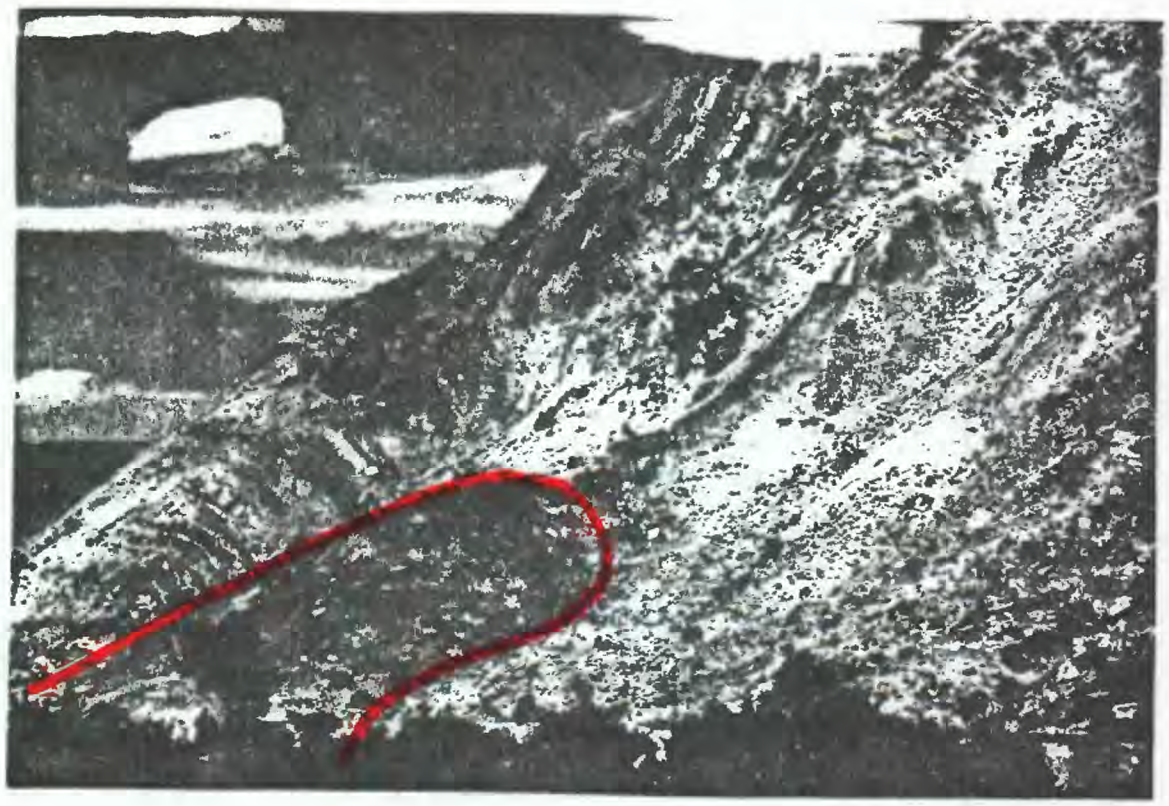


Figure 4.--Folded and faulted strata and travertine apron at Austin Springs. The apron is about 15 metres high and lies at the base of the slope to the left of the center of the picture.

Sample localities

Travertine at all sample localities is mostly calcium carbonate but commonly contains notable strontium, manganese, scandium, beryllium, or magnesium and locally contains significant barium or iron. It is usually a resistant but very porous laminated rock.

The Austin Springs area contains eroded remnants of an old travertine apron as well as newly forming aprons (fig. 5). One spring contains a purple precipitate that is particularly high in molybdenum, mercury, and sulfur. Some of the seeps at Austin Springs have produced white, evaporitic sodium chloride salts high in lithium and boron and small stalactite tubes high in strontium.

Geyser-deposited travertine is a bright rust color apparently caused by the precipitation of ferric hydroxide (fig. 6). Carbon dioxide pressure builds up in the system and causes eruptions of at least 20-minute duration several times a day. At one time pipes and valves were installed at the openings in an apparent attempt to regulate the flow, but the pipes are now rusted and the valves are ineffective.

Travertine at the mouth of Sulfur Gulch has been able to accumulate only as the cementing agent to old river gravel beds, which form coarse resistant conglomerate deposits (fig. 7). Yellowish-white, purple, rusty, and black precipitates coat the rocks at the springs in Sulfur Gulch.

Travertine deposits at the fish hatchery are inconspicuous, being generally obscured by soil and plants, but they are highly radioactive. The black precipitate here contains 46 percent sulfur and high amounts of iron and zinc.

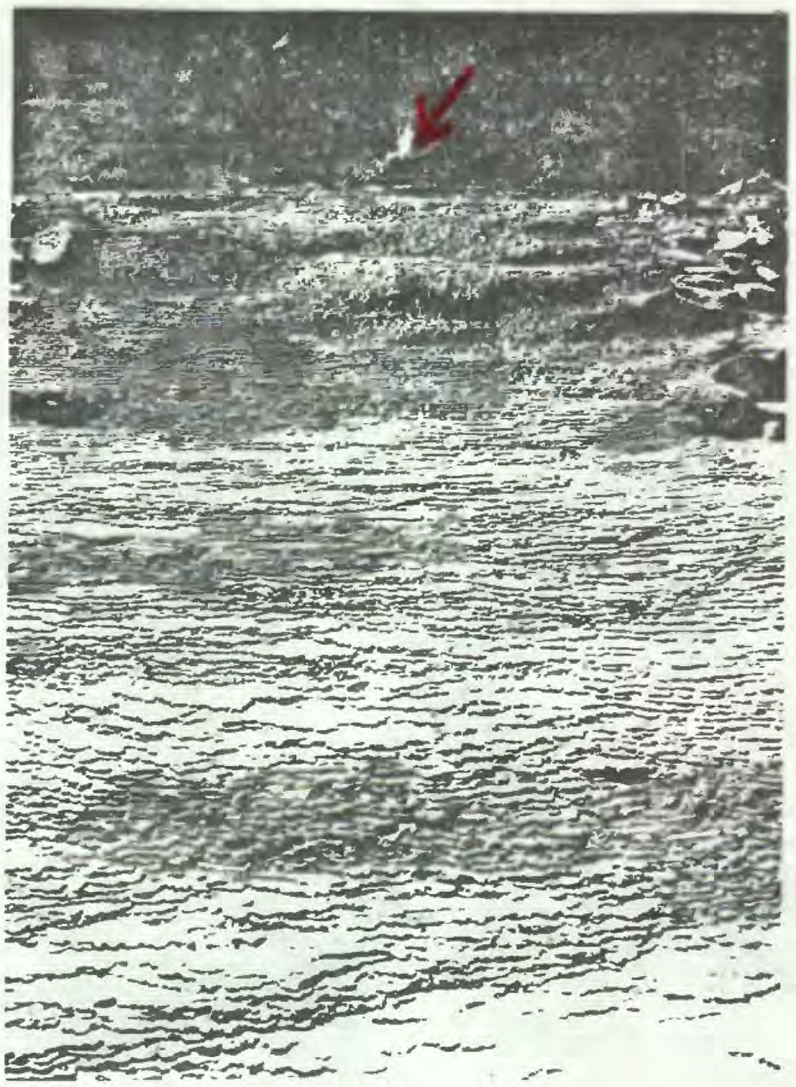
Travertine at the Doughty Springs forms a conspicuous shelf that is moderately to highly radioactive (fig. 8). Most of the radioactivity is due to the presence of radium-226 in amounts equivalent to as much as 0.55 percent uranium but averaging closer to 0.02 percent equivalent uranium. Variations in the radioactivity of the shelf as detected by scintillometer are shown in figure 9.

A

B

Figure 5.--Travertine aprons at Austin Springs. A, Eroded remnant of apron along west-facing dip-slope hillside. B, Newly forming apron in small gulley on this same hillside; note person in center of scale.

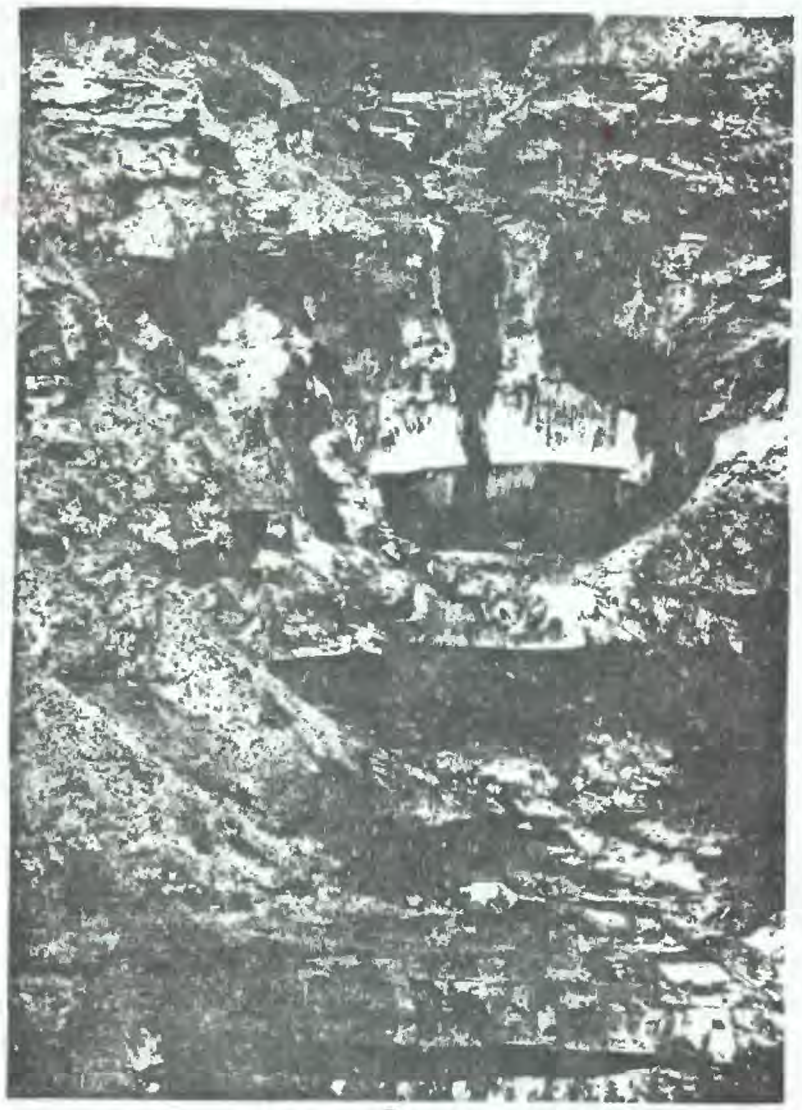
A



B

Figure 6.--Travertine deposits at the geysers. A, Eruption and surrounding ferric hydroxide bearing travertine; the water reaches heights of 1-2 metres. B, Terraces formed by downward-flowing water from the geyser during eruption.

A



B

Figure 7.--Spring deposits in Sulfur Gulch. A, Travertine-cemented stream gravel at the mouth of Sulfur Gulch. B, Precipitates coating the rocks at the spring-fed pools several hundred metres upstream from mouth of gulch.

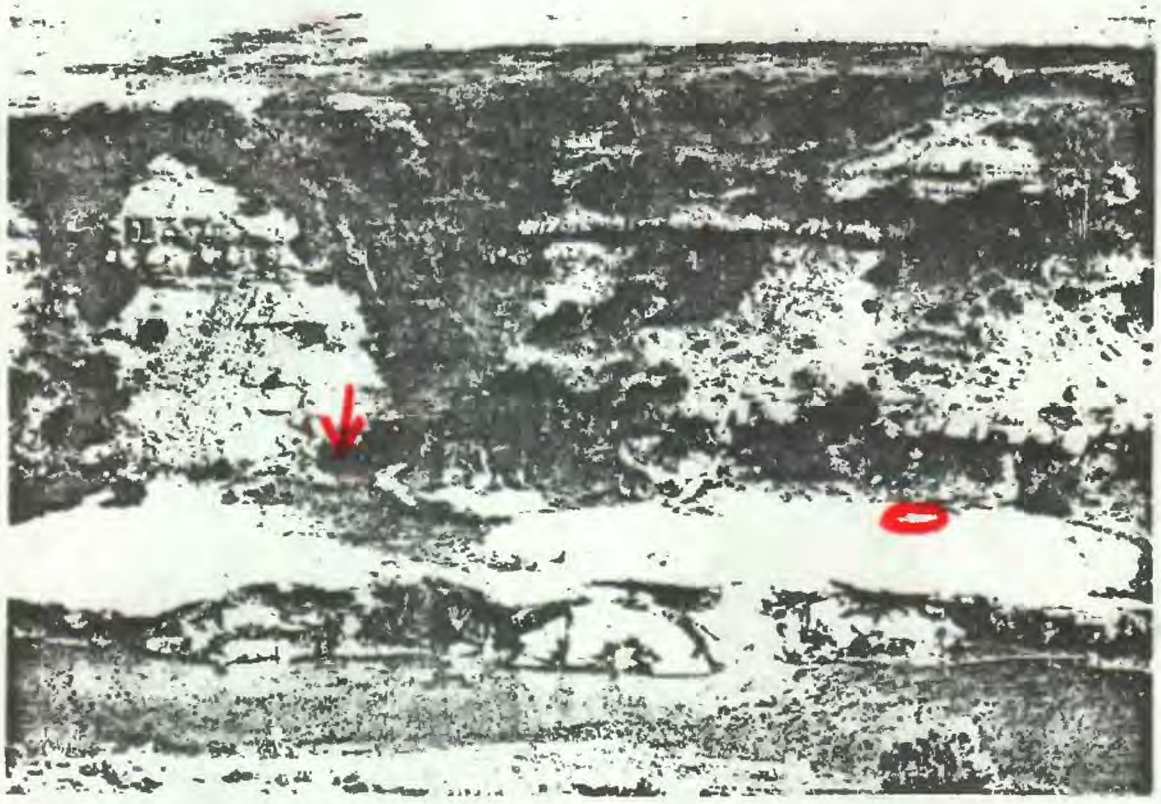


Figure 8.--Travertine shelf at Doughty Springs. The 4-metre-diameter pool at the right, just below the sandstone ledge, is the Bathtub Spring. Alum Spring is at the left, near the west end of the shelf.

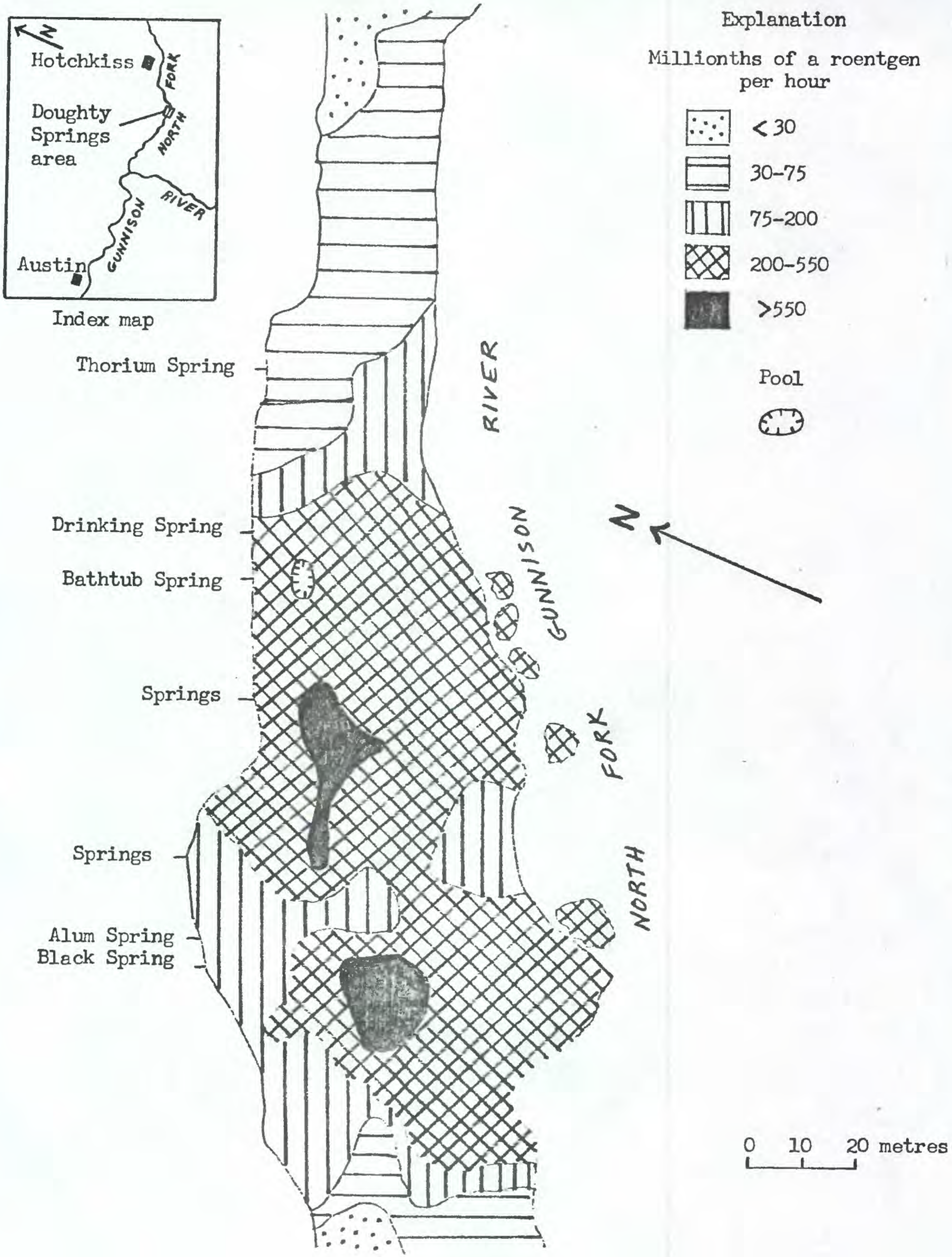


Figure 9.--Isorad map of Doughty Springs area.

Hydrogen-sulfide and sulfur-dioxide gas seeps occur at two sites--Sulfur Gulch and Doughty Springs. Surface manifestations of the seeps are the strong odor of the gases and the encrustations of native sulfur along joint faces of the Dakota Sandstone and basal carbonaceous sandstones and mudstones of the overlying Mancos Shale. Some of these sulfur-impregnated rocks have been quarried and used as a soil conditioner according to M. G. Dings (1949); the quarries in Sulfur Gulch have recently been reactivated.

Sample Analyses

Methods of analysis

To characterize the geochemical properties of the springs and their radioactive isotopes, samples of travertine, soft precipitates, muds, and water were collected. Water samples were analyzed for major ions by chemical methods, for trace elements by semiquantitative spectrography, for uranium by extraction fluorimetry, and for radium by radiochemical methods. All solid spring-related samples were analyzed for 60 elements by six-step semiquantitative spectrography and for equivalent uranium by radiometric methods. Highly radioactive samples were subjected to gamma-ray spectrometry to determine relative quantities of radioactive isotopes, and some were examined by delayed neutron techniques to determine uranium and thorium content. Mercury was measured by atomic absorption, and chlorine and sulfur, by colorimetry.

Interpretation of results

Travertine, precipitates, and muds

Results of the analyses of travertine, precipitates, and muds are given in table 1. To determine element covariance the data were tested by multivariate R-mode factor analysis. Seven major factors were identified (table 2). Each factor is interpreted as being a particular depositional process that controlled the distribution of elements within the samples. Identification of these factors shows that several processes are operating in the surface environment related to the hydrothermal system. These processes account for element associations at the surface, yet also reflect the mobility of elements in the subsurface system.

Table 1.--Analyses of spring deposits in Delta County

[All data are in parts per million. All elements except sulfur, mercury, and equivalent uranium were determined by semiquantitative spectrographic methods. Asterisk indicates arbitrary values chosen for factor analysis where the amount of element in the sample was beyond the detection limit; lower limits are shown in column headings; upper limit was 10 percent. Samples are shown in the order they are in the reordered oblique projection matrix of the 7th rotation of the Q-mode factor analysis; this ordering shows the seven factor groups as well as those samples that have a negative covariance with the other samples in the group. Elements looked for but not found in any samples are given here with their detection limits in parts per million: Ag, 0.5; Au, 20; Bi, 10; Cd, 20; Ce, 150; Hf, 1; In, 10; Nd, 70; P, 2000; Pd, 1; Pr, 100; Pt, 30; Re, 30; Sb, 150; Sm, 100; Sn, 10; Ta, 200; Te, 2000; Th, 200; Tl, 50; U, 500; W, 100; Zn, 200. Some samples were analyzed for chlorine; CD5888 has 28.5 percent Cl. Sample localities: DS, Doughty Springs; SG, Sulfur Gulch; AS, Austin Springs; G, the geysers; FH, Hotchkiss National Fish Hatchery. Analysts: L. A. Bradley, R. B. Carten, J. G. Frisken, V. James, J. C. Negri, H. G. Neiman, V. C. Smith, M. Solt, Z. C. Stephenson.]

Table 1.—Analyses of spring deposits in Rocky Mountain

Sample	Sample loc.	Latitude	Longitude	Iron (Fe) 500	Magnesium (Mg) 200	Calcium (Ca) 500	Titanium (Ti) 2	Manganese (Mn) 10	Arsenic (As) 1000	Boron (B) 20	Barium (Ba) 2
CD6107	DS	38.7700	107.7589	500	5000	200000*	15	5000	50*	1*	200000*
CD5995	DS	38.7700	107.7589	500	5000	200000*	10	5000	50*	1*	100000*
CD5997	DS	38.7700	107.7589	1500	5000	200000*	20	3000	50*	1*	70000
CD6108	DS	38.7700	107.7589	1500	5000	200000*	50	5000	50*	5*	200000*
CD5996	DS	38.7700	107.7589	3000	7000	200000*	20	2000	50*	1*	70000
CD6110	DS	38.7700	107.7589	700	7000	200000*	50	5000	50*	5*	50000
CD5998	DS	38.7700	107.7589	3000	5000	200000*	3	5000	50*	1*	70000
CD5986	DS	38.7700	107.7589	1000	5000	200000*	50	3000	50*	5*	10000
CD6109	DS	38.7700	107.7589	1000	10000	200000*	70	3000	50*	5*	50000
CD6103	DS	38.7700	107.7589	1000	7000	200000*	10	3000	50*	1*	3000
CD5999	DS	38.7700	107.7589	300	10000	200000*	30	3000	50*	5*	50000
CD6102	DS	38.7700	107.7589	500	5000	200000*	.1*	5000	50*	1*	2000
CD6106	DS	38.7700	107.7589	300	7000	200000*	.1*	5000	50*	5*	3000
CD5989	DS	38.7700	107.7589	500	15000	200000*	10	2000	50*	5*	70000
CD6101	DS	38.7700	107.7589	1000	10000	200000*	10	2000	50*	5*	300
CD6105	DS	38.7700	107.7589	1000	7000	200000*	30	7000	50*	5*	15000
CD5903	SG	38.7889	107.8412	7000	7000	200000*	1000	500	50*	30	300
CD5882	AS	38.7833	107.9367	10000	7000	70000	1500	200	50*	50	300
CD5918B	SG	38.7889	107.8412	20000	7000	70000	1500	150	50*	100	500
CD5881	AS	38.7833	107.9367	7000	7000	200000*	1500	500	50*	30	200
CD5917A	SG	38.7889	107.8412	15000	7000	200000*	1000	1000	50*	30	150
CD5918A	SG	38.7889	107.8412	20000	10000	70000	1500	200	50*	100	200
CD5912	SG	38.7889	107.8412	15000	7000	70000	700	500	50*	100	150
CD5913	SG	38.7889	107.8412	15000	10000	200000*	1500	300	50*	20	300
CD5917B	SG	38.7889	107.8412	15000	10000	200000*	1000	1500	50*	30	150
CD6191A	G	38.7811	107.9306	15000	5000	200000*	150	500	2000	70	150
CD6183	G	38.7811	107.9306	30000	2000	200000*	300	700	2000	150	50
CD6179	G	38.7811	107.9306	20000	5000	200000*	300	700	1000	100	100
CD6181	G	38.7811	107.9306	20000	3000	200000*	200	700	2000	50	70
CD6190B	G	38.7811	107.9306	15000	5000	200000*	150	500	2000	70	150
CD6180	G	38.7811	107.9306	20000	3000	200000*	200	700	2000	50	70
CD6190A	G	38.7811	107.9306	15000	5000	200000*	300	500	1500	50	70
CD6189	G	38.7811	107.9306	20000	7000	200000*	70	500	7000	150	50
CD6191B	G	38.7811	107.9306	10000	5000	200000*	200	500	1500	50	30
CD6182	G	38.7811	107.9306	15000	3000	200000*	200	500	200*	50	70
CD6188	G	38.7811	107.9306	10000	10000	200000*	100	300	1500	150	20
CD5991	FH	38.7728	107.7944	5000	1500	5000	1500	30	50*	20	200000*
CD5979	FH	38.7728	107.7944	3000	1000	3000	1500	20	50*	5*	200000*
CD6216	FH	38.7728	107.7944	5000	1500	1500	2000	20	50*	30	100000
CD5963	DS	38.7700	107.7589	15000	5000	100000	700	2000	50*	150	200000*
CD6217	DS	38.7700	107.7589	2000	700	70000	200	1000	50*	5*	200000*
CD5982	DS	38.7700	107.7589	20000	7000	200000*	700	2000	50*	100	200000*
CD5978	FH	38.7728	107.7944	5000	1500	1000	3000	50	50*	30	30000
CD6215	DS	38.7700	107.7589	1500	5000	200000*	300	1500	50*	5*	200000*
CD5902	SG	38.7889	107.8412	100	1000	1500	10	7	50*	1*	.5*
CD5990	DS	38.7700	107.7589	1500	700	50000	150	300	50*	1*	7000
CD5985	DS	38.7700	107.7589	700	200	5000	50	50	50*	1*	100000
CD5988	AS	38.7833	107.9367	700	2000	2000	50	20	50*	150	15
CD5980	FH	38.7728	107.7944	700	10000	200000*	10	500	50*	5*	1000
CD5981	FH	38.7728	107.7944	500	15000	200000*	50	100	50*	5*	1000
CD5905	SG	38.7889	107.8412	5000	500	200000*	30	10000	50*	1*	10
CD6176	AS	38.7833	107.9367	1500	7000	200000*	200	3000	50*	1*	200
CD5890	AS	38.7833	107.9367	5000	7000	200000*	700	3000	50*	30	150
CD5910	SG	38.7889	107.8412	5000	3000	200000*	150	1500	50*	5*	70
CD5907	SG	38.7889	107.8412	50000	5000	200000*	200	2000	50*	30	150
CD5908	SG	38.7889	107.8412	10000	7000	200000*	200	1500	50*	50	70
CD5911	SG	38.7889	107.8412	2000	5000	200000*	200	1500	50*	5*	70
CD5914	SG	38.7889	107.8412	5000	7000	200000*	100	1500	50*	5*	100
CD5994	SG	38.7889	107.8412	7000	7000	200000*	700	2000	50*	50	300
CD6177	AS	38.7833	107.9367	200000*	5000	200000*	500	10000	1500	100	300
CD5977	FH	38.7728	107.7944	20000	5000	500	3000	50	50*	70	20000
CD5987	DS	38.7700	107.7589	1000	15000	200000*	70	3000	50*	5*	30000
CD5891	AS	38.7833	107.9367	7000	5000	200000*	300	2000	50*	30	1500
CD5889	AS	38.7833	107.9367	7000	7000	200000*	300	3000	50*	30	100
CD5998	DS	38.7700	107.7589	50000	15000	200000*	50	3000	50*	50	1500
CD6100	DS	38.7700	107.7589	2000	15000	200000*	10	3000	50*	5*	15000
CD6137	DS	38.7700	107.7589	200	10000	200000*	10	3000	50*	30	100000
CD6104	DS	38.7700	107.7589	300	10000	200000*	5	3000	50*	1*	3000
CD5906	SG	38.7889	107.8412	50000	5000	200000*	700	1500	50*	20	200
CD6216	DS	38.7700	107.7589	70000	500	3000	1000	700	50*	150	700
CD5992	FH	38.7728	107.7944	70000	3000	20000	1500	500	50*	5*	7000
CD5884	AS	38.7833	107.9367	30000	5000	30000	1500	200	50*	50	300
CD5892	AS	38.7833	107.9367	1500	5000	200000*	200	150	50*	1*	70
CD6187	G	38.7811	107.9306	10000	5000	200000*	700	500	50*	1*	200
CD6172	AS	38.7833	107.9367	700	10000	200000*	50	10000	50*	1*	70
CD6186	G	38.7811	107.9306	15000	3000	200000*	500	700	50*	1*	150
CD6173	AS	38.7833	107.9367	300	10000	200000*	10	1000	50*	1*	100
CD6175	AS	38.7833	107.9367	150	10000	200000*	5	5000	50*	1*	30
CD6178	AS	38.7833	107.9367	1000	20000	200000*	100	5000	50*	1*	100
CD6174	AS	38.7833	107.9367	300	7000	200000*	5	5000	50*	1*	30

Table 1.—Analyses of spring deposits in Doña County—Continued

Sample	Beryllium (Be) 1	Cobalt (Co) 3	Chromium (Cr) 1	Copper (Cu) 1	Lanthanum (La) 30	Molybdenum (Mo) 3	Niobium (Nb) 10	Nickel (Ni) 5	Lead (Pb) 10	Scandium (Sc) 5
CD6107	15	.15*	1	.2*	1.5*	.15*	.5*	.2*	.5*	70
CD5995	15	.15*	1	.2*	1.5*	.15*	.5*	.2*	.5*	70
CD5997	20	.15*	3	.2*	1.5*	.15*	.5*	.2*	.5*	70
CD6108	20	.15*	1	.2*	1.5*	.15*	.5*	.2*	.5*	100
CD5996	10	.15*	2	.2*	1.5*	.15*	.5*	.2*	.5*	70
CD6110	15	.15*	1	.2*	1.5*	3	.5*	.2*	.5*	70
CD5998	10	.15*	1.5	.2*	1.5*	.15*	.5*	.2*	.5*	50
CD5986	7	.15*	1.5	2	1.5*	.15*	.5*	.2*	.5*	50
CD6109	10	.15*	2	.2*	1.5*	.15*	.5*	.2*	.5*	70
CD6103	10	.15*	1	.2*	1.5*	.15*	.5*	.2*	.5*	70
CD5999	10	.15*	1	.2*	1.5*	.15*	.5*	.2*	.5*	50
CD6102	10	.15*	1	.05*	1.5*	.15*	.5*	.2*	.5*	150
CD6106	20	.15*	.2*	.05*	1.5*	.15*	.5*	.2*	.5*	50
CD5989	7	.15*	1.5	.2*	1.5*	.15*	.5*	.2*	.5*	30
CD6101	5	.15*	1	.2*	1.5*	.15*	.5*	.2*	.5*	20
CD6105	20	.15*	1	.2*	1.5*	.15*	.5*	.2*	.5*	50
CD5903	.05*	.7*	30	7	1.5*	.7*	2*	20	15	5
CD5882	2	.7*	30	15	7*	.7*	2*	15	50	20
CD5918B	7	7	70	20	50	3	2*	15	20	15
CD5881	3	.7*	30	10	7*	.7*	2*	10	30	30
CD5917A	10	5	30	7	7*	.7*	2*	15	10	20
CD5918A	10	7	50	30	50	3	2*	15	15	15
CD5912	20	7	20	7	7*	5	2*	10	15	20
CD5913	.05*	7	30	10	7*	.15*	2*	15	15	7
CD5917B	15	7	30	5	7*	.15*	.5*	10	10	20
CD6191A	10	.15*	2	1	1.5*	.7*	.5*	.2*	.5*	.2*
CD6183	50	.15*	2	1	1.5*	3	.5*	5	.5*	.2*
CD6179	30	.15*	2	2	1.5*	3	.5*	.2*	.5*	.2*
CD6181	20	.15*	2	3	1.5*	10	.5*	.2*	.5*	.2*
CD6190B	10	.15*	2	1	1.5*	5	.5*	1*	.5*	.2*
CD6180	20	.15*	2	3	1.5*	.15*	.5*	.2*	.5*	.2*
CD6190A	7	.15*	2	1.5	1.5*	7	.5*	.2*	.5*	.2*
CD6189	50	.15*	.05*	2	1.5*	.7*	.5*	.2*	.5*	.2*
CD6191B	10	.15*	5	.2*	1.5*	.15*	.5*	.2*	.5*	.2*
CD6182	15	.15*	2	2	1.5*	3	.5*	5	.5*	.2*
CD6188	15	.15*	.05*	.2*	1.5*	5	.5*	.2*	.5*	.2*
CD5991	.2*	.15*	30	3	1.5*	.15*	2*	.2*	.5*	30
CD5979	.05*	.15*	30	3	7*	.15*	2*	.2*	10	20
CD6218	.05*	.15*	30	7	7*	.15*	2*	.2*	10	15
CD5983	20	.15*	15	7	1.5*	.15*	.5*	1*	10	100
CD6217	3	.15*	2	2	1.5*	.15*	.5*	.2*	.5*	70
CD5982	15	.15*	15	15	1.5*	.15*	.5*	1*	10	100
CD5978	3	.7*	30	7	7*	.15*	2*	1*	15	20
CD6218	15	.15*	5	1.5	1.5*	.15*	.5*	.2*	.5*	100
CD5902	.05*	.15*	1	.2*	1.5*	.15*	.5*	.2*	.5*	.2*
CD5990	1.5	.15*	2	3	1.5*	.15*	.5*	.2*	.5*	10
CD5985	.05*	.15*	1.5	1	1.5*	.15*	.5*	.2*	.5*	5
CD5988	.05*	.15*	1.5	1	1.5*	.15*	.5*	1*	.5*	.2*
CD5980	.05*	.15*	2	.2*	1.5*	.15*	.5*	.2*	.5*	.2*
CD5981	.05*	.15*	2	1	1.5*	.15*	.5*	.2*	.5*	.2*
CD5905	.05*	.15*	3	.2*	1.5*	.15*	.5*	.2*	.5*	.2*
CD6176	7	.15*	5	1.5	1.5*	15	.5*	.2*	.5*	100
CD5890	7	.15*	15	3	1.5*	.15*	.5*	1*	15	70
CD5910	15	.15*	7	2	1.5*	.15*	.5*	5	.5*	50
CD5907	30	.7*	7	3	1.5*	5	.5*	10	.5*	50
CD5908	15	.7*	10	3	1.5*	.15*	.5*	7	.5*	15
CD5911	15	.15*	7	3	1.5*	.15*	.5*	1*	.5*	70
CD5914	10	.7*	7	2	1.5*	.15*	.5*	1*	.5*	30
CD5994	30	.15*	20	7	1.5*	.15*	.5*	5	2*	100
CD6177	7	.7*	7	2	1.5*	.15*	.5*	5	10	100
CD5977	2	.15*	70	15	70	10	10	7	20	15
CD5987	7	.15*	3	1.5	1.5*	.15*	.5*	.2*	.5*	30
CD5891	3	.15*	7	3	1.5*	.15*	.5*	1*	.5*	30
CD5889	5	.15*	7	3	1.5*	.15*	.5*	5	.5*	30
CD5998	15	.15*	1	.2*	1.5*	.15*	.5*	.2*	.5*	50
CD6100	10	.15*	1.5	.2*	1.5*	.15*	.5*	.2*	.5*	50
CD6137	7	.15*	1	.05*	1.5*	.15*	.5*	.2*	.5*	30
CD6104	15	.15*	1	.05*	1.5*	.15*	.5*	.2*	.5*	70
CD5906	30	5	15	7	7*	3	2*	15	2*	70
CD6216	10	.15*	20	15	7*	7	2*	1*	30	15
CD5992	2	5	20	30	1.5*	3	2*	15	15	15
CD5884	3	5	20	20	7*	50	2*	15	30	15
CD5892	1.5	.15*	7	2	1.5*	.15*	.5*	1*	.5*	30
CD6187	7	.15*	10	5	1.5*	.15*	.5*	.2*	10	.2*
CD6172	7	.15*	1	1.5	1.5*	.15*	.5*	.2*	.5*	70
CD6186	10	.15*	7	3	1.5*	.7*	.5*	.2*	.5*	.2*
CD6173	2	.15*	.05*	.05*	1.5*	.15*	.5*	.2*	.5*	30
CD6175	7	.15*	.05*	5	1.5*	.15*	.5*	.2*	.5*	70
CD6178	5	.15*	1	.2*	1.5*	.7*	.5*	.2*	.5*	50
CD6174	7	.15*	.05*	.05*	1.5*	.15*	.5*	.2*	.5*	100

Table 1.—Analyses of spring deposits in Delta County—Continued

Sample	Strontium (Sr) 5	Vanadium (V) 7	Yttrium (Y) 10	Zircon (Zr) 10	Silicon (Si) 20	Aluminum (Al) 100	Sodium (Na) 500	Potassium (K) 7000	Gallium (Ga) 5	Germanium (Ge) 10
CD6107	5000	.3*	20	.5*	1000	1000	3000	300 *	.2*	.5*
CD5995	5000	.3*	.5*	.5*	1500	1500	3000	300 *	.2*	.5*
CD5997	3000	.3*	15	.5*	1500	2000	3000	300 *	.2*	.5*
CD6108	5000	1.5*	30	.5*	3000	3000	3000	300 *	.2*	.5*
CD5996	3000	.3*	.5*	.5*	2000	2000	5000	300 *	.2*	.5*
CD6110	5000	.3*	20	.5*	3000	2000	10000	300 *	.2*	2 *
CD5998	3000	.3*	.5*	.5*	1000	3000	5000	300 *	.2*	.5*
CD5986	5000	.3*	10	.5*	7000	2000	5000	300 *	.2*	2 *
CD6109	5000	.3*	30	.5*	3000	3000	10000	300 *	.2*	2 *
CD6103	5000	.3*	20	.5*	500	500	15000	300 *	.2*	.5*
CD5999	5000	.3*	.5*	.5*	2000	1500	7000	300 *	.2*	2 *
CD6102	3000	.3*	50	.5*	100	200	10000	300 *	.2*	.5*
CD6106	5000	.3*	20	.5*	1500	500	7000	300 *	.2*	.5*
CD5989	5000	.3*	.5*	.5*	1500	1500	7000	300 *	.2*	.5*
CD6101	2000	.3*	2*	.5*	1000	1000	7000	300 *	.2*	.5*
CD6105	7000	10	.5*	.5*	5000	1000	7000	300 *	.2*	10
CD5903	7000	50	15	70	70000	50000	30000	20000	7	.5*
CD5882	1500	70	15	150	200000 *	50000	20000	30000	10	.5*
CD5918B	700	100	30	150	200000 *	70000	15000	30000	15	.5*
CD5881	1500	70	15	100	200000 *	30000	20000	30000	10	.5*
CD5917A	15000	70	30	50	70000	50000	20000	30000	7	30
CD5918A	700	100	30	150	200000 *	70000	15000	30000	15	.5*
CD5912	1500	50	20	70	200000 *	30000	7000	300 *	15	10
CD5913	1500	70	15	70	200000 *	50000	15000	30000	10	.5*
CD5917B	10000	70	30	50	70000	50000	10000	15000	7	20
CD6191A	7000	5	.5*	30	20000	7000	30000	300 *	.2*	.5*
CD6183	5000	5	.5*	10	10000	5000	50000	300 *	.2*	.5*
CD6179	5000	10	.5*	20	20000	7000	50000	1500 *	.2*	.5*
CD6181	5000	.3*	.5*	10	10000	3000	30000	300 *	.2*	.5*
CD6190B	7000	10	.5*	70	10000	3000	30000	300 *	.2*	.5*
CD6180	5000	.3*	.5*	10	5000	5000	20000	300 *	.2*	.5*
CD6190A	7000	10	.5*	200	10000	5000	30000	300 *	.2*	.5*
CD6189	10000	.3*	.5*	.5*	5000	3000	30000	300 *	.2*	.5*
CD6191B	7000	.3*	.5*	50	5000	2000	30000	300 *	.2*	.5*
CD6182	5000	5	.5*	30	15000	7000	30000	300 *	.2*	.5*
CD6188	10000	.3*	.5*	.5*	3000	1500	30000	300 *	.2*	.5*
CD5991	2000	70	15	150	200000 *	30000	5000	7000	10	2 *
CD5979	1000	50	15	100	200000 *	30000	5000	10000	10	.5*
CD6218	2000	70	15	150	200000 *	70000	2000	7000	10	.5*
CD5983	5000	50	50	50	70000	30000	10000	7000	7	10
CD6217	3000	15	50	200	50000	7000	2000	300 *	.2*	.5*
CD5982	5000	50	50	70	70000	50000	20000	7000	5	10
CD5978	300	100	20	150	200000 *	70000	3000	10000	15	.5*
CD6215	10000	20	30	15	10000	15000	7000	300 *	1 *	2 *
CD5902	70	.3*	.5*	.5*	700	700	200000 *	300 *	.2*	.5*
CD5990	150	1.5*	10	.5*	20000	3000	2000	300 *	.2*	.5*
CD5985	2000	.3*	.5*	.5*	3000	1000	3000	300 *	1*	.5*
CD5988	150	7	.5*	.5*	10000	3000	200000 *	7000	.2*	.5*
CD5980	700	.3*	.5*	.5*	1000	300	5000	300 *	.2*	.5*
CD5981	500	.3*	.5*	.5*	3000	1000	3000	300 *	.2*	2*
CD5905	200	.3*	70	.5*	2000	3000	3000	300 *	.2*	.5*
CD6176	2000	15	20	70	30000	10000	7000	300 *	.2*	.5*
CD5890	7000	30	20	70	70000	30000	20000	15000	7	.5*
CD5910	15000	30	30	30	15000	7000	10000	300 *	.2*	15
CD5907	7000	70	70	30	50000	15000	10000	300 *	7	50
CD5908	3000	50	15	30	20000	15000	10000	300 *	1 *	20
CD5911	3000	30	30	30	50000	15000	7000	300 *	1 *	.5*
CD5914	10000	30	50	.5*	7000	5000	15000	300 *	.2*	.5*
CD5994	2000	100	70	70	100000	20000	20000	7000	7	15
CD6177	1000	150	20	70	50000	20000	10000	300 *	10	200
CD5977	100	150	30	200	200000 *	100000	3000	50000	30	.5*
CD5987	5000	.3*	2*	.5*	5000	3000	10000	300 *	.2*	2*
CD6191	20000	30	15	30	30000	15000	20000	300 *	.3*	30
CD5989	7000	50	10	30	70000	15000	30000	300 *	1*	30
CD5998	2000	.3*	30	.5*	7000	2000	30000	300 *	.2*	10
CD6100	5000	.3*	20	.5*	2000	1000	15000	300 *	.2*	.5*
CD6137	5000	.3*	.5*	.5*	2000	1000	30000	300 *	.2*	.5*
CD6104	5000	.3*	15	.5*	2000	1000	10000	300 *	.2*	2*
CD5906	1000	70	200	100	70000	15000	15000	7000	7	30
CD6216	150	70	50	150	200000*	70000	2000	300 *	15	.5*
CD5992	200	20	15	100	50000	15000	5000	300 *	7	15
CD5984	300	50	20	150	200000*	50000	15000	20000	15	.5*
CD5992	5000	15	2*	30	20000	10000	7000	300*	.2*	.5*
CD6167	5000	30	.5*	150	50000	20000	20000	7000	5	.5*
CD6172	5000	10	.5 *	.5*	5000	2000	20	20000	.2*	.5*
CD6186	5000	20	.5 *	70	30000	15000	20000	1500*	1*	.5*
CD6173	15000	.3 *	.5 *	.5 *	1000	1500	20000	300*	.2*	.5*
CD6175	5000	20	.5 *	.5 *	500	1000	7000	300*	.2*	.5*
CD6178	7000	.3 *	.5 *	.5 *	7000	3000	10000	300*	.2*	.5*
CD6174	5000	15	.5 *	.5 *	700	1000	7000	300*	.2*	.5*

Table 1.—Analyses of spring deposits in Delta County—Continued

Sample	Lithium (Li) 50	Ytterbium (Yb) 1	Sulfur (S) ---	Mercury (Hg) 0.02	Equivalent uranium (eU) 30
CD6107	2*	.2*	19600	.04	450
CD5995	2*	.05*	6500	.02	270
CD5997	2*	.05*	7000	.005*	240
CD6108	2*	1.5	26300	.005*	500
CD5996	2*	.05*	6300	.02	200
CD6110	2*	.2*	9400	.10	260
CD5988	2*	.2*	6400	.001*	250
CD5986	2*	.2*	14700	.04	140
CD6109	2*	.2*	9700	.04	300
CD6103	2*	.2*	2090	.02	50
CD5999	2*	.05*	7800	.04	90
CD6102	2*	2	5800	.2	60
CD6106	2*	.2*	6700	.06	40
CD5989	2*	.05*	7000	.02	140
CD6101	2*	.05*	5300	.04	70
CD6105	2*	.2*	3080	.1	70
CD5903	2*	1.5	10500	.3	60
CD5882	10*	2	2960	.06	7*
CD5918B	150	3	2900	.10	7*
CD5881	10*	1.5	3160	.06	7*
CD5917A	10*	2	600	.10	40
CD5918A	200	3	3400	.10	7*
CD5912	500	2	12600	.06	50
CD5913	2*	1.5	1700	.06	7*
CD5917B	10*	3	5500	.04	7*
CD6191A	2*	.05*	6000	.001*	80
CD6183	10*	.05*	10000	.001*	60
CD6179	2*	.05*	9000	.001*	50
CD6181	2*	.05*	10000	.001*	30
CD6190B	2*	.05*	7000	.02	70
CD6180	2*	.05*	10000	.005*	30
CD6190A	2*	.05*	6000	.001*	60
CD6189	150	.05*	7000	.001*	90
CD6191B	2*	.05*	7000	.02	40
CD6182	2*	.05*	10000	.005*	7*
CD6188	150	.05*	6000	.001*	60
CD5991	2*	1.5	65000	.06	2500
CD5979	2*	1.5	53000	.02	2200
CD6218	2*	1.5	23000	.03	950
CD5983	200	5	58000	.02	1100
CD6217	2*	2	402000	.03	2270
CD5982	300	3	59000	.06	600
CD5978	2*	3	10700	.02	70
CD6215	2*	2	35900	.01	974
CD5902	2*	.05*	200000	.005*	7*
CD5990	2*	.2*	630000	.26	70
CD5985	2*	.2*	590000	1.00	500
CD5988	700	.05*	11000	.005*	7*
CD5980	2*	.05*	5200	.005*	7*
CD5981	2*	.05*	4500	.005*	7*
CD5905	2*	7	190	.005*	7*
CD6176	2*	.05*	700	.02	7*
CD5890	100	1.5	1700	.02	7*
CD5910	2*	2	7800	.10	60
CD5907	2*	5	6000	.06	30
CD5908	2*	.05*	4000	.02	7*
CD5911	10*	2	140000	.12	7*
CD5914	2*	2	9200	.02	7*
CD5994	10*	5	12300	.04	50
CD6177	2*	.05*	800	.02	60
CD5977	200	5	11000	.26	230
CD5987	200	.2*	6100	.02	70
CD5891	150	1.5	1540	.001*	7*
CD5889	200	1	1700	.02	50
CD5998	200	1.5	5600	.04	7*
CD6100	200	.05*	4320	.04	70
CD6137	150	.05*	10500	.10	180
CD6104	100	1	5100	.04	60
CD5906	2*	10	130000	.40	7*
CD6216	2*	3	140000	.06	20
CD5992	2*	1.5	460000	.38	50
CD5884	10*	2	90400	1.20	7*
CD5892	2*	.05*	1300	.02	7*
CD6167	2*	.05*	7000	.02	40
CD6172	2*	.05*	1000	.005*	7*
CD6186	2*	.05*	10000	.02	7*
CD6173	2*	.05*	200	.001*	1.5*
CD6175	2*	.05*	2000	.001*	80
CD6178	2*	.05*	1000	.001*	7*
CD6174	2*	.05*	1000	.005*	7*

Table 2.--Results of element factor analysis

Contamination by sand and silt	Precipitation of salts	Precipitation of carbonates	Coprecipitation with barium	Contamination by clay	Precipitation of sulfides	Coprecipitation with iron
1	2	3	4	5	6	7
Al	Li	Mn	eU	La	Hg	Mo
V	B	Be	Ba	Nb	Y	As
Si	(Be)	Ca	(Be)	Mg	Yb	Fe
Ti	(Sr)	Sc	(Sc)	(K)	S	(Cu)
Cu	(Mg)	Sr	(S)	(Zr)	Co	(B)
Cr	(Na)	(Mg)	(As)	(Pb)	Ni	(Be)
Ga	(Ge)	(Ge)		(Ba)	(Cr)	(Na)
K	(As)	(Y)			(Ga)	(S)
Zr	(Fe)				(Sc)	(Co)
Pb					(Ba)	(Ni)
(B)					(Ge)	
(Sr)						
(Ge)						
(Y)						
(Yb)						
(Co)						
(Ni)						
(Fe)						

The seven factors account for 78 percent of the correlation matrix variance. The element at the top of each column coincides with the factor axis, and the elements are listed by decreasing order of their degree of covariance with the axis element. Elements in parentheses are minor elements of the group and occur as major elements in other groups; for example, boron, a minor element in the factor-1 group, is a major element in the factor-2 group. Factor 1 is the most important process or event in terms of its effect on the covariance of the metals, and the other factors follow in decreasing order of importance. The titles are the interpretation; the groups are the mathematical results.

The seven factors in decreasing order of importance are as follows: intermixture of detrital sand and silt with the spring deposits by talus creep, stream action, or wind; precipitation of light-metal salts, apparently chlorides and borates, as a result of evaporation; precipitation of carbonates; precipitation of barium sulfate and coprecipitation of radium; intermixture of clay minerals with the spring deposits by soil wash or in situ formation; precipitation of sulfides of heavy metals; and precipitation of ferric hydroxide and the coprecipitation of associated elements.

Some factor groups have a more obvious interpretation than others. The close relationship between radioactivity, as measured by equivalent uranium, and barium in factor 4, for example, is easily interpreted as the coprecipitation of barium and radium in the spring deposits. On the other hand, the coprecipitating elements in factor 7 suggest only tentative interpretations. These elements are extremely mobile; they may come into solution as a result of alteration and leaching of deposits in the subsurface hydrothermal system and precipitate at the surface as a result of any number of changes in the geochemical environment, including change in Eh or pH, loss of carbon dioxide or hydrogen sulfide gas pressure, or simple evaporation. Some elements are lost from solution in many forms; sulfur, for example, is lost as hydrogen sulfide, native sulfur, sulfate, and sulfide or sulfosalts.

To determine sample grouping and possible geographic differentiation, the 80 by 33 data matrix was tested by Q-mode factor analysis. The first seven computed factors were selected for interpretation of sample groupings; they account for 77 percent of the total variance. Factors 1 and 6 contain groups with strong negative loadings in the reordered oblique projection matrix. These two negative groupings are also considered as factor groups for our purposes and are identified as groups 8 and 9 respectively.

Seven of the nine sample groups are varieties of travertine, and two are varieties of precipitates. The travertines are typical travertine of calcium carbonate and associated elements; travertines containing ferric hydroxide coprecipitates, namely arsenic and molybdenum; travertine containing sodium and lithium salts; travertine containing radioactive barite; and travertine mixed with sedimentary detritus. The precipitates are sulfur-rich precipitates and light-metal salt precipitates.

The sample groups are partly related to geographic location; hence, areal variations in the geochemistry of the system can be identified, as shown in table 3. Travertine containing radioactive barite is found only at two adjacent localities, Doughty Springs and the fish hatchery. Travertine containing iron hydroxide coprecipitates is restricted to the geysers. Travertine containing lithium and sodium salts is found at Doughty Springs and Austin Springs. Detritus and light-metal and sulfur-rich precipitates are found at most localities.

Water

Water samples were collected and analyzed to determine the major and minor element content of the water associated with the spring deposits. Results of the analyses are given in tables 4 and 5. Chemical analyses of major ions show that, in all springs but one, sodium is the dominant cation and bicarbonate or chloride is the dominant anion.

The one spring that is not a bicarbonate or chloride water is the Alum Spring at Doughty Springs (fig. 10). This acid-sulfate water has a pH of 2.9 and contains high concentrations of several minor elements.

Table 3.--Results of sample factor analysis

Locality	Major sample types	Significant minor elements
Austin Springs------	Travertine; salt and sulfur precipitates.	Na, Li, B, Hg, Mo
Geysers----------	Travertine containing iron coprecipitates.	Fe, As, Mo, Be, B
Sulfur Gulch--------	Travertine; sulfur precipitates.	S
Fish hatchery-------	Travertine containing radioactive barite.	Ba, eU
Doughty Springs-----	Travertine containing radioactive barite.	Ba, eU

Table 4.--Analyses of springs in Delta County

A. Chemical analyses, in milligrams per litre

Sample	Date of colln.	lat	long	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Chloride (Cl)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Dissolved solids ROE	Dissolved solids Sum	Hardness Ca-Mg	Hardness Non-carbonate	Specific conductivity (μmhos at 25°C)	Water temperature (°C)	pH
DEL1	7-24-70	38.7833	107.9367	17	230	240	3100	81	2400	1750	217	2800	0.9	<0.10	0.11	9740	9960	1600	0	13800	16	9.0
DEL2	7-24-70	38.7833	107.9367	10	150	50	4500	130	4000	4300	0	1500	1.8	3.80	.25	12700	12500	590	0	18400	16	9.2
DEL3	9-10-72	38.7833	107.9367	--	---	---	----	---	----	----	---	----	---	----	----	-----	-----	----	---	-----	--	---
DEL4	9-10-72	38.7889	107.8412	--	---	---	----	---	----	----	---	----	---	----	----	-----	-----	----	---	-----	--	---
DEL5	9-10-72	38.7889	107.8412	--	---	---	----	---	----	----	---	----	---	----	----	-----	-----	----	---	-----	--	---
DEL6	9-12-73	38.7700	107.7589	17	110	43	1100	47	720	2150	0	94	2.5	.01	.12	3420	3190	450	0	5000	15	6.5
DEL7	9-12-73	38.7700	107.7589	--	---	---	----	---	----	----	---	----	---	----	----	-----	-----	----	---	-----	--	---
DEL8	9-12-73	38.7700	107.7589	--	---	---	----	---	----	----	---	----	---	----	----	-----	-----	----	---	-----	--	---
DEL9	9-12-73	38.7700	107.7589	60	170	98	180	22	25	0	0	1500	.7	.48	.18	2120	2130	830	830	2600	14	2.9
DEL10	8-30-74	38.7728	107.7944	38	98	140	560	28	320	1290	0	620	1.6	.00	.25	3440	2440	820	0	3300	13	6.3
DEL11	5-21-75	38.8333	107.6500	25	110	34	610	36	370	1540	0	58	2.4	.01	.12	3120	2010	410	0	3200	41	6.6

B. Spectrographic analyses, in micrograms per litre

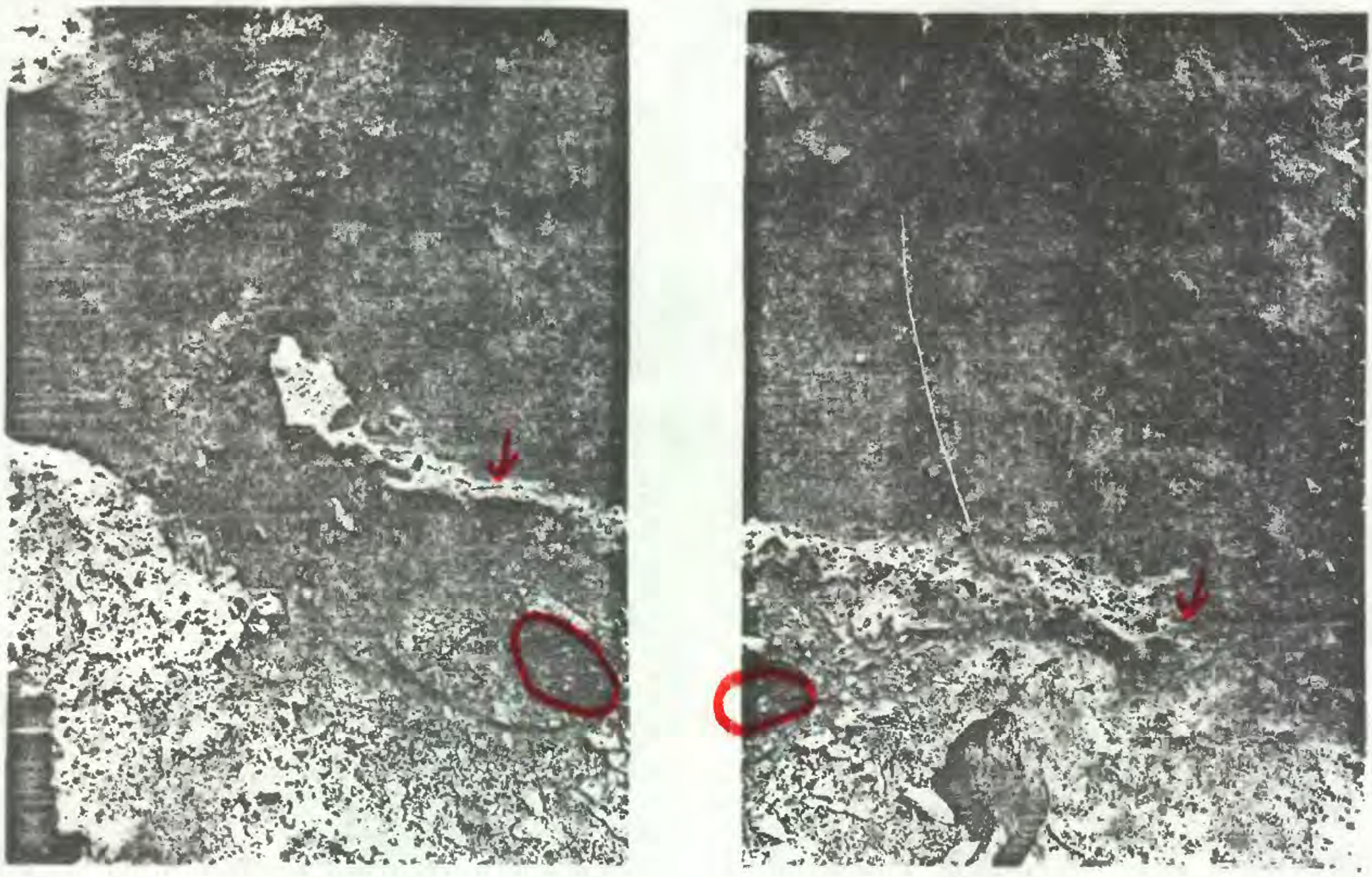
Sample	Aluminum (Al)	Antimony (Sb)	Arsenic (As)	Barium (Ba)	Beryllium (Be)	Bismuth (Bi)	Boron (B)	Cadmium (Cd)	Chromium (Cr)	Cobalt (Co)	Copper (Cu)	Gallium (Ga)	Germanium (Ge)	Iron (Fe)	Lead (Pb)	Lithium (Li)	Manganese (Mn)	Molybdenum (Mo)	Nickel (Ni)	Silver (Ag)	Strontium (Sr)	Tin (Sn)	Titanium (Ti)	Vanadium (V)	Zinc (Zn)	Zirconium (Zr)
DEL1	290	<0.5	110	<19	1	<10	3100	<5	<.2	<2	350	<76	<190	680	1	5300	920	16	<2	<.2	7200	<1800	<2	<820	<10	4
DEL2	60	<0.5	210	<24	1	<10	4800	<5	.7	<2	170	<97	<250	700	2	4000	1300	.7	<2	<.2	7700	<2300	<2	<1100	<10	9
DEL3	1200	<5	250	<540	<2	<1	5900	<5	<3	<5	27	<120	<250	750	4	10000	320	20	<11	<2	2800	----	22	<120	<100	22
DEL4	380	<5	<5	<250	26	<1	3200	<5	<3	<5	10	<55	<120	200	1	6400	860	5	<11	<2	4300	<120	<11	<55	<100	<5
DEL5	530	<5	180	<350	<2	<1	1600	<5	<3	<5	18	<75	<160	440	1	4000	360	33	11	<2	6600	<100	<11	<75	<160	<5
DEL6	75	<5	<46	3500	2	<.3	5300	<10	<1	<3	<10	<22	<50	<10	<3	3400	660	<.5	<5	<.3	3600	<50	<1	<20	<22	<1
DEL7	100	<5	<46	340	3	<.3	5100	<10	2	<3	<11	<25	<50	<10	<3	3100	850	<.5	<5	<.3	3000	<50	3	<22	<22	<1
DEL8	750	<5	<46	150	5	<.3	1100	<10	2	<3	<10	<20	<45	2800	<3	2300	820	.5	<5	<.3	2700	<45	<1	<20	<22	<1
DEL9	10000	<5	<46	37	12	<.3	330	<10	26	<22	40	<14	<30	47000	10	190	1200	.7	15	<.3	900	<5	26	<13	510	12
DEL10	20	----	---	17	<6	<17	770	<20	<8	<16	<4	<4	<16	860	<16	2000	860	<6	<6	<2	1100	<6	<11	<8	<20	<16
DEL11	55	----	---	4000	<5	<15	800	<1	<15	<15	<3	<7	<15	<15	<15	1500	700	<3	<15	<2	3100	<15	<7	<10	<1	<20

Sample localities

DEL1: Austin Springs; northern spring, at base of sandstone outcrop, near irrigation ditch; NW¼SE¼SE¼ sec. 31, T. 14 S., R. 94 W.
DEL2: Austin Springs; southern spring, on hillside at top of travertine apron; NW¼NE¼NE¼ sec. 6, T. 15 S., R. 94 W.
DEL3: Austin Springs; northern spring.
DEL4: Sulfur Gulch; spring-fed pool in gulch; NE¼SW¼SE¼ sec. 36, T. 14 S., R. 94 W.
DEL5: Sulfur Gulch; spring-fed pool in gulch.
DEL6: Doughty Springs; small spring that drains into Bathtub Spring; NE¼NW¼NW¼ sec. 11, T. 15 S., R. 93 W.
DEL7: Doughty Springs; spring northwest of Bathtub Spring.
DEL8: Doughty Springs; spring northwest of Bathtub Spring.
DEL9: Doughty Springs; Alum Spring, clear spring that drains into Black Spring at west end of travertine shelf.
DEL10: Hotchkiss National Fish Hatchery; spring in old adit; NE¼SW¼SE¼ sec. 3, T. 15 S., R. 93 W.
DEL11: Col. Chinn artesian well; cased well near farm house; SW¼NE¼NE¼ sec. 14, T. 14 S., R. 92 W.

Table 5.--Results of water analyses

Locality	Water type	Significant minor elements
Austin Springs, northern-----	$Na-Cl-SO_4$	Li, B, Al, As, Cu, Ti, Zn
Austin Springs, southern-----	$Na-Cl-HCO_3$	Li, B, As, Cu
Sulfur Gulch----------	----------	Li, B, Al, As, Be, Y
Fish hatchery adit spring----	$Na-Mg-HCO_3-SO_4$	Li
Col. Chinn well----------	$Na-HCO_3-Cl$	Li, Ba
Doughty Springs, Bathtub-----	$Na-HCO_3-Cl$	Li, B, Al, Ba
Doughty Springs, Alum--------	$H-Ca-Mg-Na-SO_4$	Al, Fe, Cr, Pb, Zn, Ti, Y



A B

Figure 10.--Alum Spring at Doughty Springs. White sulfate precipitates (A) line the path of this acid water above point (B) where black sulfide precipitates form as a result of changes in pH and other solution equilibrium reactions. Note camera in same position in both pictures.

Water from the Alum Spring resembles closely the ore-transporting fluids described by H. L. Barnes and G. K. Czamanske (1967). Water emerging from Alum Spring may be typical of the subsurface water of the whole hydrothermal system, but at this specific spring the results of changes in equilibrium can be observed at the surface. Observable products of the changes in equilibrium are sulfur in both gaseous and precipitated form--sulfur dioxide and hydrogen sulfide, and barite and black metal sulfides.

The products suggest that the solutions contain a variety of sulfur-based ions such as $S_x^{=}$, HSO_3^{-}, HS_x^{-}, and metal ions such as Fe^{++}, Ra^{++}, Al^{+++}, Ba^{++}. The solutions lose equilibrium as the result of oxidation of the sulfur complexes and expansion and loss of gases with accompanying decrease in temperature.

Suggested reactions in probably oversimplified form are illustrated by the following formulas:

$$2H_2S + 4O_2 \longrightarrow 2HSO_3^{-} + H_2O,$$

representing a near-surface oxidation reaction in which bisulfite ion is produced;

$$2HS^{-} + 3O_2 \longrightarrow SO_2 + S + H_2O,$$

representing oxidation of the bisulfide radical to yield sulfur dioxide gas and sulfur emanations; and

$$2Fe(HS)_2 + O_2 \longrightarrow FeS + 2H_2O + 2S,$$

representing oxidation of ferrous bisulfide to yield ferrous sulfide and sulfur precipitates. The deposition of precipitated barite, with which radium is coprecipitated, may result either from a change in equilibrium of an acid solution in which barium sulfate is carried in solution or from oxidation of the bisulfite anion:

$$6HSO_3^{-} + 4Ba^{++} \longrightarrow H_2S + 2H_2O + 4BaSO_4 + S.$$

White sulfates form along the path of the drainage of Alum Spring, and then black metal sulfides precipitate abruptly in the pool (Black Spring) below (fig. 10). Reddish-brown iron oxides form on the surface of the Black Spring and stain the calcite-barite travertine south of the spring.

Comparison of analyses from Delta County (table 4) with those from nearly 100 other springs in Colorado, as reported by Mallory and Barnett (1973), shows that the Delta County springs are typical in some respects and atypical in others. Lithium is high in all samples, and boron is high in samples from Austin Springs, Sulfur Gulch, and Doughty Springs. Aluminum is high in most samples from these three localities, and, in fact, is higher than in any samples reported by Mallory and Barnett. Arsenic is high in all samples from Austin Springs and Sulfur Gulch and is the highest in the State in some samples. Levels of barium in one of the Doughty Springs and in the Col. Chinn well are by far the highest reported for any springs in Colorado.

The element contents of the water show a general correlation with the precipitates at the various localities, although some differences are apparent. Lithium and boron are high in nearly all the waters but appear significantly in the precipitates only at some localities, apparently where evaporation allows some salts to form. Arsenic is abundant in water at Austin Springs, Sulfur Gulch, and presumably the geysers; however, it only shows up in the precipitates at the geysers, where it is associated with ferric hydroxide, a substance not precipitating at Sulfur Gulch or Austin Spring. Aluminum is high in many water samples but does not show significantly in the precipitated samples used in the factor analyses. One notable occurrence of an aluminum-rich precipitate is found in Alum Gulch, a north-flowing tributary that enters the North Fork of the Gunnison River just downstream from Doughty Springs (fig. 11). There, as mentioned in Headden's (1905) report, a one-half-metre-thick deposit of alunite, a hydrous potassium aluminum silicate, has formed from water seeping out at the base of the Dakota Sandstone. Such natural surface occurrences are rare and are one additional indication that the hydrothermal solutions are high in aluminum.

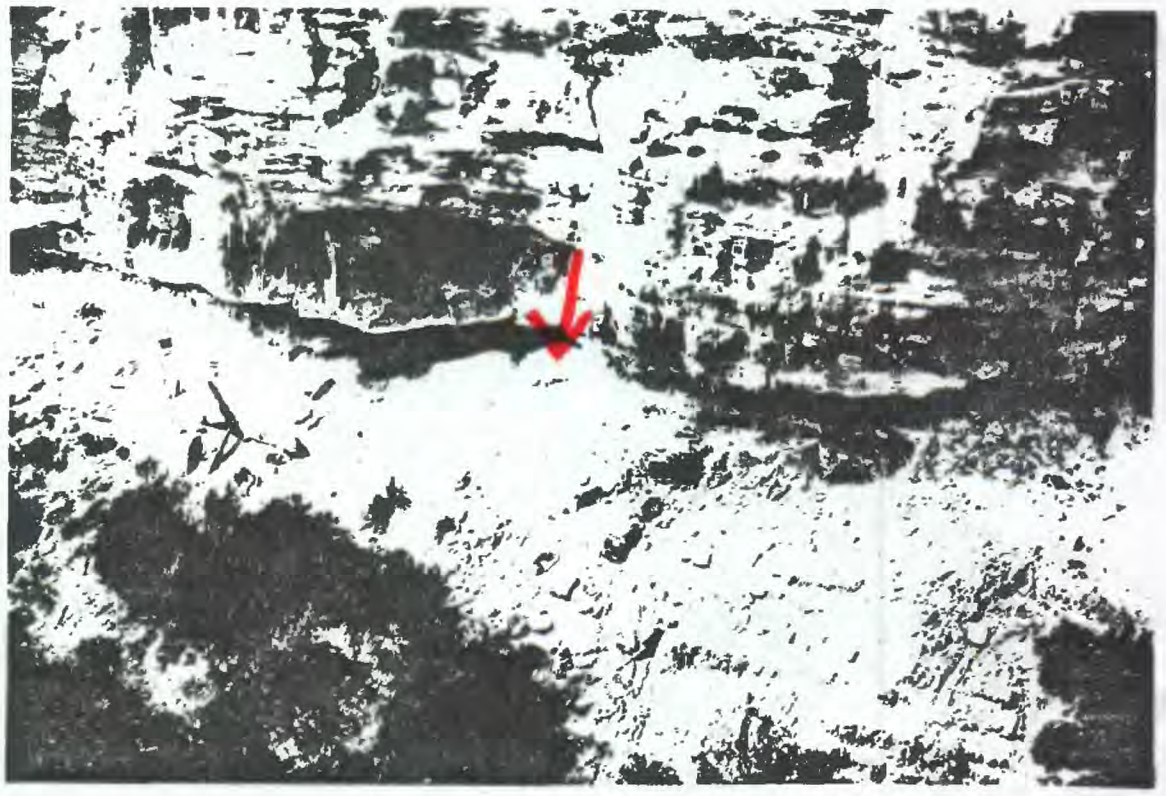


Figure 11.--Alum Gulch alunite deposit. The deposit forms a white powdery to crystalline crust at the contact between the Morrison Formation and the Dakota Sandstone.

Radioactivity

The radioactive spring deposits and water are confined to the eastern part of the study area--Doughty Springs, the fish hatchery, and the Col. Chinn well. The radioactivity is due principally to the presence of radium-226, the daughter product of uranium-238. Field observations suggest and factor analysis confirms that the radium coprecipitates with barium sulfate.

Water from the radioactive sites contains 0.55 to 9.1 picocuries per litre or micromicrograms per litre radium and 0.03 and 4.5 parts per billion or micrograms per litre uranium (table 6). These concentrations are not particularly high compared with published and unpublished data on concentrations of radium and uranium in other springs and wells in Colorado. The significant feature of the radioactive elements is their lack of equilibrium. Radium and uranium are present in equilibrium amounts in only one sample, the acid-sulfate water of Alum Spring. The bicarbonate-sulfate water contains radium that is enriched four times over its equilibrium concentration with the uranium, and the bicarbonate-chloride water contains radium enriched 10 to nearly 1,000 times over its equilibrium concentration. It appears that water higher in bicarbonate and chloride and lower in sulfate is more likely to contain a higher concentration of radium, if a source of radium--that is, a subsurface concentration of uranium--is intersected by the hydrothermal pipeline.

Disequilibrium between uranium and radium is even greater in the precipitates than in the water (table 7). Seven samples of radioactive precipitate from Doughty Springs and the fish hatchery contain radium in concentrations about 500 to 8,000 times more than the equilibrium value for the uranium present. Some of the uranium that gave rise to this radium probably is transported in solution into the Gunnison River, but much of it, we believe, still remains in the source rock or in the related hydrogeologic plumbing.

Table 6.--Radioactivity of water

Locality	Radium (μμg/l)	Uranium (μg/l)	Radium enrichment factor[1]	Dominant anions
Doughty Springs, Alum-----	1.5	4.5	1	SO_4
Fish hatchery adit spring-	.55	.45	4	HCO_3-SO_4
Doughty Springs, Bathtub--	2.9	.45	15	HCO_3-Cl
Col. Chinn well----------	9.1	.03	880	HCO_3-Cl

[1]The number of times the radium-uranium ratio in the sample exceeds the radium-uranium ratio at equilibrium. The factor is calculated by 2.9×10^6 (Ra/U), where Ra is the amount of radium in the sample, in micromicrograms per litre, and U is the amount of uranium in the sample, in micrograms per litre.

Table 7.--Radium and uranium in precipitates

Locality	Sample no.	RaeU[1] (ppm)	Uranium (ppm)	Radium enrichment factor (RaeU/U)
Fish hatchery-----	CD5979	4830	2.76	1750
	CD5991	5500	2.47	2230
Doughty Springs---	CD5982	2720	2.66	1020
	CD5983	3690	2.04	1810
	CD5985	1000	2.13	470
	CD6107	1130	.37	3050
	CD6108	1830	.22	8320

[1]Radium equivalent uranium, the amount of uranium that would be required for radioactive equilibrium with the amount of radium actually in the sample, as determined by gamma-ray spectrometry.

The precipitates contain more thorium than uranium, as determined by delayed neutron analysis, and probably reflect an abundance of thorium over uranium in the source rocks. Five samples average nearly twice as much thorium as uranium (table 8). One highly radioactive soft precipitate from a small spring east of the main shelf at Doughty Springs (fig. 12) was analyzed by J. N. Rosholt and C. M. Bunker using gamma-ray spectrometry. It contains some radium-226, the daughter product of uranium-238, but consists mainly of radium-228 and and its daughter thorium-228, both daughter products of thorium-232 (fig. 13). The sample contains radium-226 in an amount that would require 0.18 percent uranium-238 for equilibrium support, radium-228 in an amount requiring 0.75 percent thorium-232 for support, and thorium-228 in an amount requiring 0.40 percent thorium-232. Lack of equilibrium between radium-228 and its daughter thorium-228 indicates that the sample, which is a precipitate that is still forming, has been accumulating over the last 2 to 2 1/2 years and had an original amount of radium-228 requiring 0.87 percent thorium-232 for equilibrium support. The high original ratio of radium-228 to radium-226 in this sample, a ratio of nearly 5 to 1, indicates that the radioactive source minerals for this spring are higher in thorium than in uranium, a feature more typical of vein-type than of sandstone-type uranium deposits.

Table 8.--Thorium and uranium in precipitates

Locality	Sample no.	Thorium (ppm)	Uranium (ppm)	Thorium/ uranium
Fish hatchery-----	CD5977	18.41	12.14	1.52
	CD5979	5.00	2.76	1.81
	CD5991	5.38	2.47	2.18
Doughty Springs---	CD5982	5.26	2.66	1.98
	CD5983	4.03	2.04	1.98

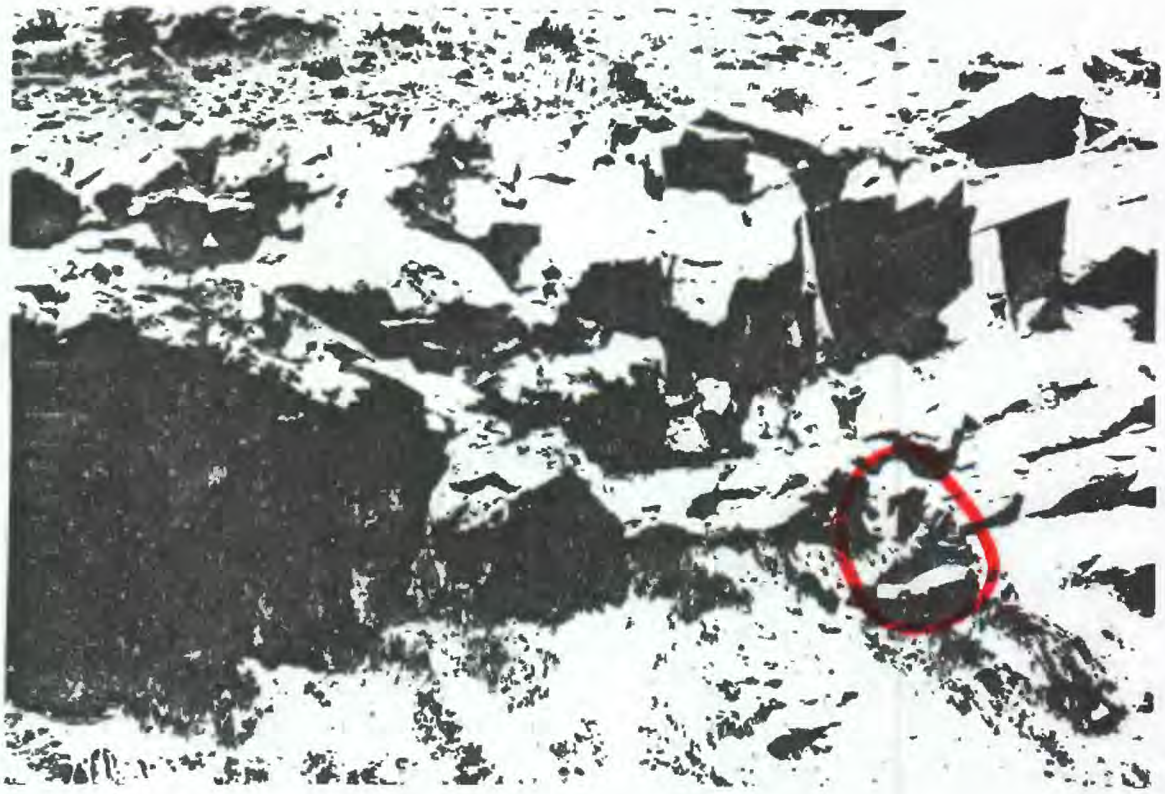


Figure 12.--Thorium spring at Doughty Springs. The spring is one of numerous points of issue along sandstone bedding planes on the cliff east of the main travertine shelf. Person at lower right is pointing to spring.

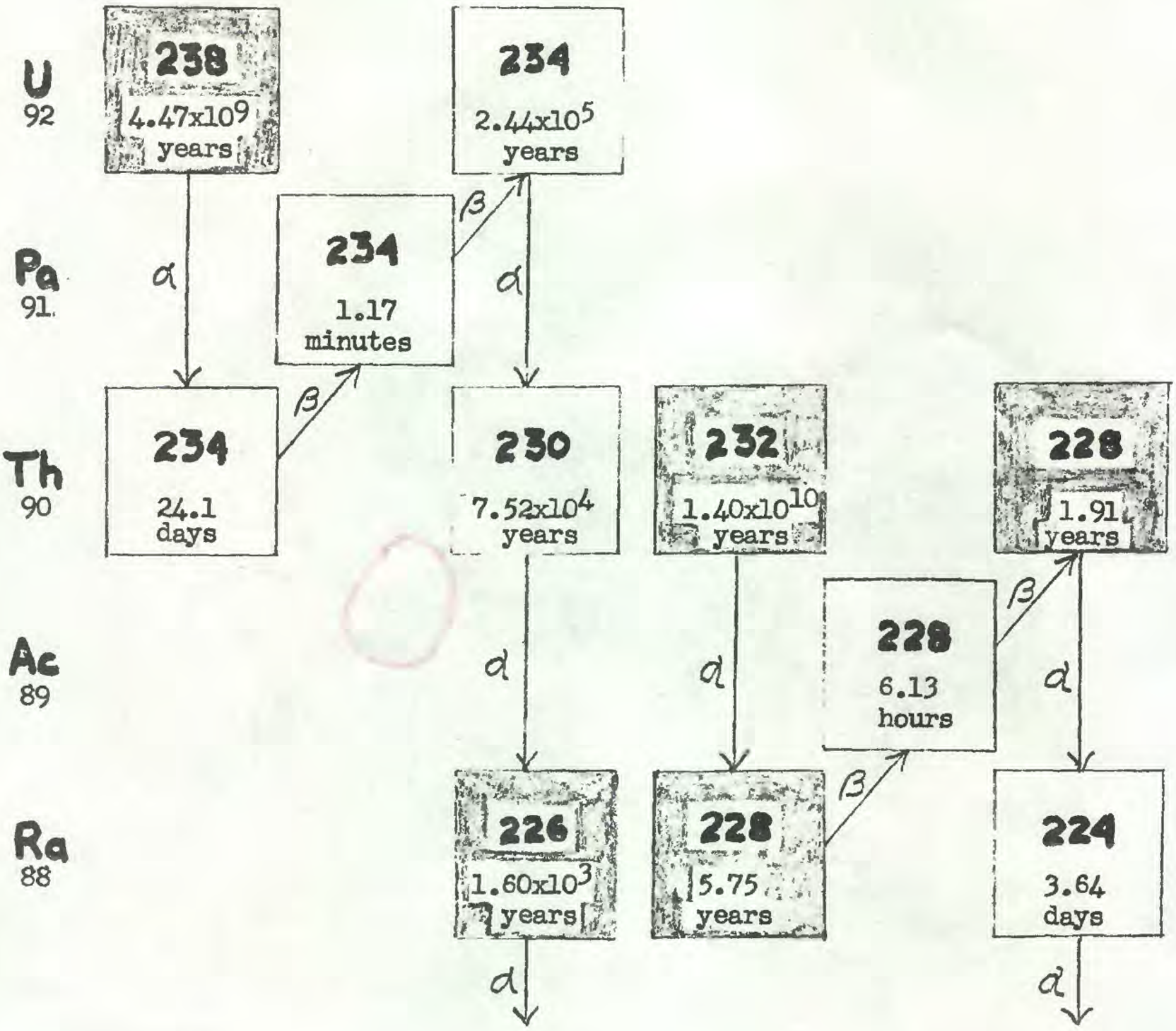


Figure 13. Uranium-238 and thorium-232 isotopic disintegration series. Only the daughter products through radium are shown. Isotopes in the shaded boxes are those detected in precipitates at Doughty Springs. Numbers in the boxes are half lives of the isotopes.

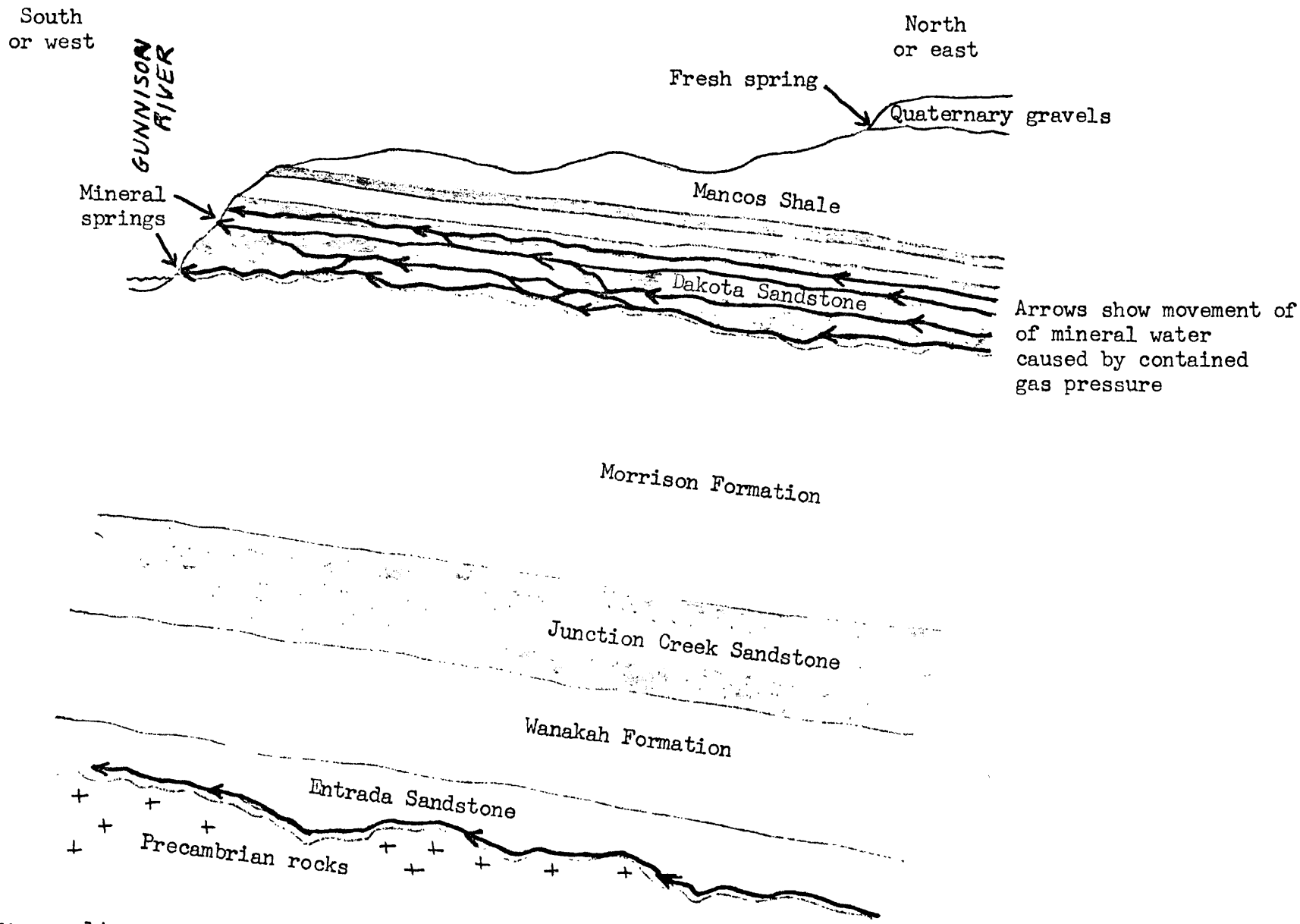


Figure 14.--Diagrammatic section showing hypothetical flow of ground water in south-central Delta County, Colorado.

Conclusions

The location of the mineral deposits that supplied the radioactive elements to these springs is still speculative. Fresh water is available in large quantities at the fish hatchery and on the mesas to the north from a perched water table in the Quaternary deposits overlying the Mancos (fig. 14). This water does not intermix with the gaseous hydrothermal solutions flowing along the parting and bedding planes of sandstones in the basal Mancos Shale, in the Dakota Sandstone, and along the disconformity at the top of the Morrison Formation. (The hydrothermal pipeline may also include the Jurassic-Precambrian unconformity; at this contact in the Gunnison River canyon at the mouth of Smith Fork is a breccia cemented with an unusual calcite-barite matrix reminiscent of the composition of some travertine.) The rate of movement of the mineral water is unknown, but the volume of flow for the whole study area--estimated to be on the order of 250,000 gallons per day--indicates a fairly rapid rate. In the Hotchkiss area the movement, under pressure of expanding gases, is apparently updip and generally from east to west.

Relations of older travertine aprons to the geomorphology of the area suggest that the age of the springs and the hydrothermal system is in the range from 50,000 to 200,000 years before present. The warm (41°C) temperature of water at the Col. Chinn well near Paonia suggests that the source of hydrothermal activity is in the eastern part of the area, perhaps within 5 to 20 kilometres of the well.

The large quantities of radium that have been deposited in the springs or transported into the Gunnison River while the springs have been active suggest that proportionately large quantities of uranium remain in the igneous source rock or in deposits associated with the hydrothermal pipeline, possibly at depth.

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