FIELDNOTES
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THERMAL SPRINGS OF ARIZONA

by James C. Witcher

Identification of truly *thermal* springs is an indispensable aid in the assessment of a region's geothermal characteristics. Over the years numerous lists of thermal springs in Arizona have been compiled and we present yet another. Although the word thermal implies heat, there is considerable subjectivism or arbitrariness in its application. In geothermal work what is important is anomalous or unusual heat—something above a norm. A functional scheme has been devised that is useful in identifying those Arizona springs judged to be carrying anomalous heat. The method is readily applied to any new springs that may be encountered. The results of this updated version are shown in Table 1. Also, possible heat sources are briefly outlined in the text.

Defining Thermal Springs

Over the years, springs given the label "thermal" may or may not carry anomalous heat. Likewise, it is possible for springs not so labeled to be anomalously warm. The explanation for this is not difficult; it is to be found in Arizona's regional topographic-climatic variances.

Depending upon the season, the temperature of the earth down to 10 or 20 meters is slightly above or below the mean annual air temperature (MAT). Because springs are surface discharges of water contained in the pores and fractures of rock at very shallow depth, springs tend to have a temperature close to the MAT. Spring temperatures that are much higher than the MAT are thermal springs and their waters are heated by anomalously hot rock near the surface or by circulation through hot rock at much greater depths.

The MAT in Arizona ranges from less than 6°C to over 22°C, primarily because the surface elevation is quite varied; therefore, a similar range in spring temperatures is to be expected. Generally, a thermal spring at a high elevation will have a lower temperature than an equally significant thermal spring at a lower elevation where the MAT is higher. Thus, the MAT provides a baseline from which a thermal spring can be defined from place to place.

However, in order to actually classify a spring as being thermal, some comparisons, or temperature standard above the baseline temperature, is needed. This comparison temperature should fall somewhere between normal spring temperatures and those that are anomalously high and obviously thermal. The temperature distribution of Arizona's springs relative to the mean annual air temperature (MAT) is utilized to find this comparison temperature.

Spring temperatures measured during field work and reported in geologic literature covering Arizona were compiled. All available MAT data for Arizona were plotted and contoured on a map of Arizona in order to determine the MAT at the spring locations. The MAT for individual spring locations is subtracted from the individual measured spring temperatures and plotted on a frequency diagram in Figure 1. A mostly normal distribution of spring temperatures relative to the MAT is evident. The mean spring temperature is slightly above the MAT. This mean spring temperature relates to the average circulation depth of these waters below the surface.

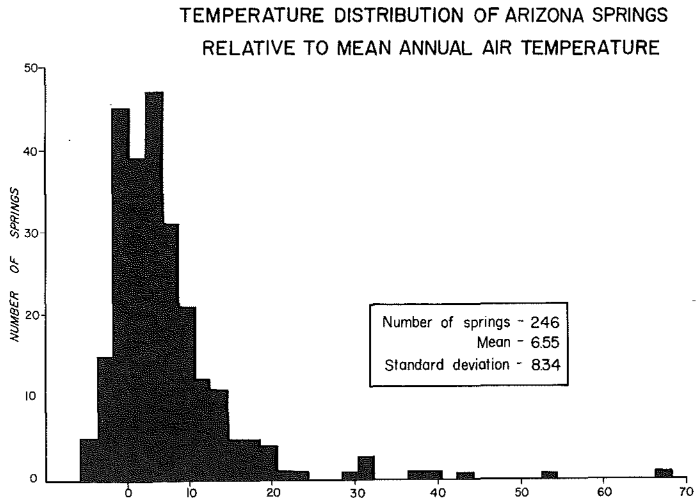
TEMPERATURE DISTRIBUTION OF ARIZONA SPRINGS RELATIVE TO MEAN ANNUAL AIR TEMPERATURE

Figure 1. SPRING TEMPERATURE MINUS MEAN ANNUAL AIR TEMPERATURE (°C)

However, the distribution is not perfectly normal when all springs in Arizona are considered. Actually, the distribution appears to have two means with similar standard deviations. When the mean spring temperature of the Basin and Range province is compared to the mean spring temperature of the Colorado Plateau province (Figure 2), a bimodal mean spring temperature is evident, the former being the higher. If the same average circulation depth and average rock thermal conductivities are assumed for both provinces, the difference may relate to the higher conductive heat flow observed in the Basin and Range province. If this is true, the higher mean spring temperature of the Basin and Range springs is caused by a higher average subsurface temperature gradient. It should be pointed out that other explanations are plausible such as differences in surface vegetative cover, average spring flow rates, and seasonal recharge.

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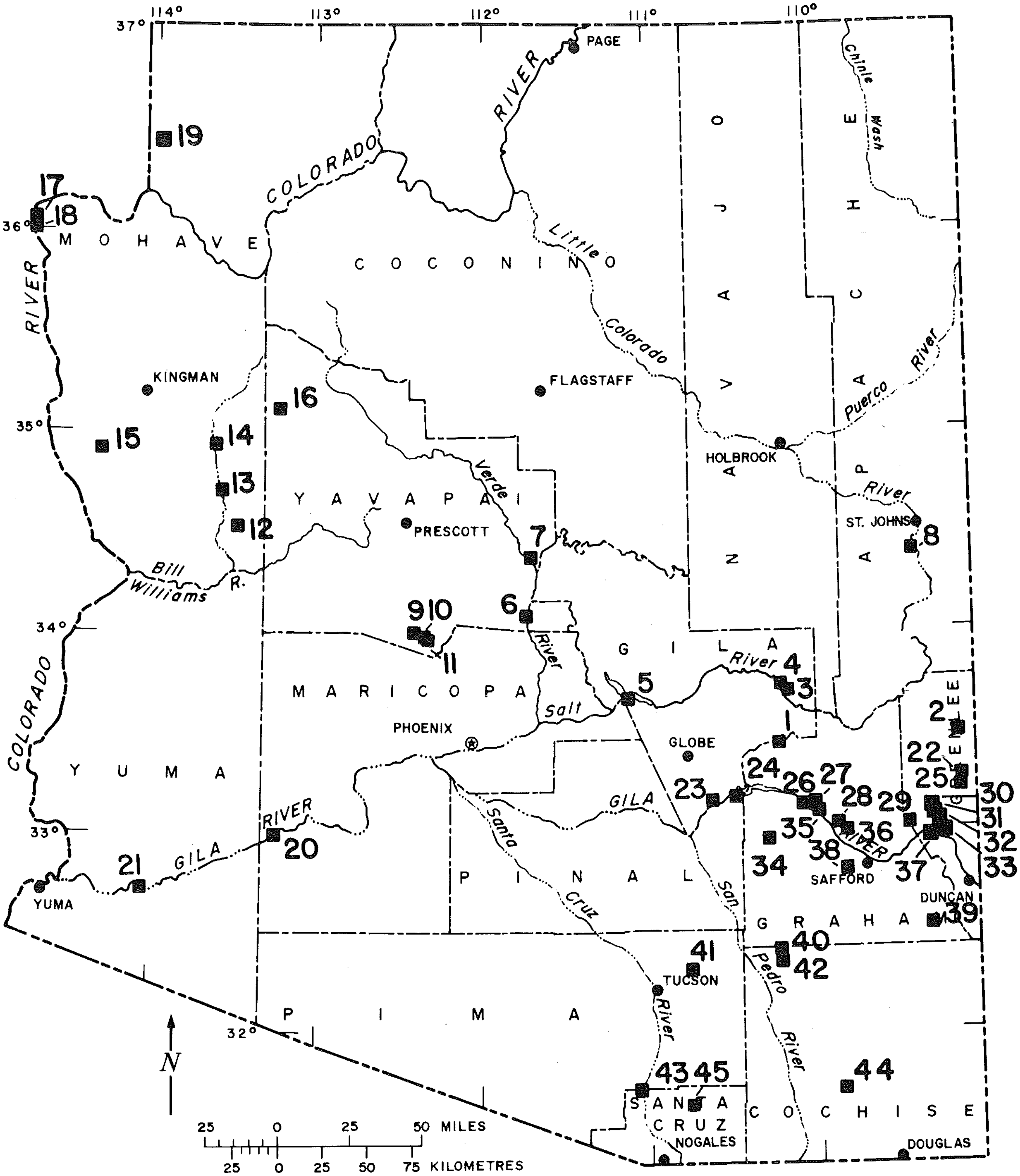

The apparent deviation of spring temperatures below the mean , assuming a normal distribution, is believed to be caused by discharge from perched water tables close to recharge sources and not discharge from the static water table.

Thermal waters may be subdivided arbitrarily into "hot" and "warm." Hot springs for all of Arizona are here defined as those having temperatures that exceed the MAT by the sum of the mean spring temperature for all springs and the standard deviation (Figure 1). Thus, the comparison temperature used to define a *hot spring* is 15°C above a spring's MAT. In the Basin and Range province the comparison temperature used to define a "warm spring" is 10°C above the appropriate MAT. For the Colorado Plateau province 6°C above the MAT defines a "warm spring" (Figure 2). These definitions apply only to Arizona and may vary in

THERMAL SPRINGS OF ARIZONA

#	NAME	LOCATION	T°C	T-MAT°C
1	Warm Spring	A-1-20-12AC*	29.4	14.4
2	Hanna Creek Hot Springs	A-1-31-29AD	55.5	42.5
3	Warm Spring	A-4½-20-36CB*	24.4	10.4
4	White River Salt Spring	A-4½-20-35AD*	28.3	13.3
5	Roosevelt Dam Hot Spring	A-4-12-19DDB	48.0	28.0
6	Hot Spring	A-9-6-26AB*	36.6	17.6
7	Verde Hot Springs	A-11-6-3B	41.0	23.0
8	Salado Spring	A-12-28-17DCA	21.7	11.7
9	Henderson Ranch Spring	B-8-1-33BAC	30.3	11.3
10	Alkalai Spring	B-8-1-33DB	31.2	12.2
11	Castle Hot Springs	B-8-1-34CC	54.7	35.7
12	Kaiser Hot Spring	B-14-12-10AD	37.0	19.0
13	Cofer Hot Spring	B-16-13-25CAD	37.0	18.0
14	Warm Spring	B-18-13-25DB	28.3	10.3
15	Warm Spring	B-18-19-33DC	29.2	10.2
16	Spring	B-20-9-30CC	27.0	14.0
17	Hot Spring	B-30-23-15CBD	32.0	12.0
18	Hot Spring	B-30-23-26BBC	30.0	10.0
19	Pakoon Spring	B-35-16-24BD	28.0	10.0
20	Agua Caliente Spring	C-5-10-19AA	40.0	18.0
21	Radium Hot Spring	C-8-18-12CC	60.0	38.0
22	Spring	D-2-31-35ABB*	25.6	10.6
23	Mescal Warm Spring	D-3-17-20CBC	29.1	14.0
24	Coolidge Dam Hot Spring	D-3-18-17DC	36.6	18.6
25	Miguel Raton Spring	D-3-31-3ADC	26.7	11.7
26	Spring	D-4-23-21AA	27.2	10.2
27	Spring	D-4-23-21AD	31.5	14.5
28	Tom Niece Spring	D-4-23-22BD	28.3	11.3
29	Eagle Creek Hot Spring	D-4-28-35ABB	42.5	25.5
30	Clifton Hot Spring	D-4-30-18CCD	70.0	53.0
31	Clifton Hot Spring	D-4-30-18CDC	50.0	33.0
32	Clifton Hot Spring	D-40-30-19CAA	33.0	16.0
33	Clifton Hot Spring	D-4-30-30DBC	38.0	21.0
34	Warm Spring	D-5-19-23BDD	26.0	11.0
35	Indian Hot Springs	D-5-24-17AD	48.8	30.8
36	Spring	D-5-24-16CB	33.0	16.0
37	Gillard Hot Spring	D-5-29-27AAD	84.0	67.0
38	Spring	D-7-24-13DC	29.4	12.4
39	Spring	D-10-29-23DD	26.1	10.1
40	Spring	D-12-21-31CA	32.5	17.5
41	Agua Caliente Spring	D-13-16-20CDD	32.0	12.0
42	Hookers Hot Spring	D-13-21-6AAC	52.0	37.0
43	Agua Caliente Spring	D-20-13-13BA	27.0	11.0
44	Antelope Spring	D-20-24-21DC	25.5	10.5
45	Monkey Spring	D-21-16-3C	28.3	13.3

*Unsurveyed

other states having different geological terrains and subsurface geophysical properties.

Origin of Thermal Springs

Thermal springs, as herein defined, originate from a combination of special conditions. These conditions are basic elements in any geothermal system and they have to work in concert before a system can exist naturally. These elements are: (1) a heat source; (2) a recharge source; (3) a circulation framework or storage reservoir; and (4) a discharge mechanism.

The most basic element is the heat source because it alone separates geothermal spring systems from all others. In Arizona, igneous heat sources are tentatively ruled out because no Recent or Pleistocene silicic volcanism is known. Silicic magma is very viscous and tends to collect in large shallow storage sites. These bodies of magma contain enormous quantities of heat and may require several hundred thousand years to cool to ambient temperature, thereby providing significant heat to overlying rocks and contained fluids.

Recent and Pleistocene basaltic volcanism is known in Arizona; but intrusions related to this volcanism are small plugs, dikes and sills, because basaltic magma is very fluid. Small plugs, dikes and sills cool to ambient temperature in a few months or years and contribute only minor quantities of heat to the surrounding rocks.

A COMPARISON OF TEMPERATURE DISTRIBUTION OF SPRINGS IN THE COLORADO PLATEAU AND BASIN AND RANGE PROVINCES

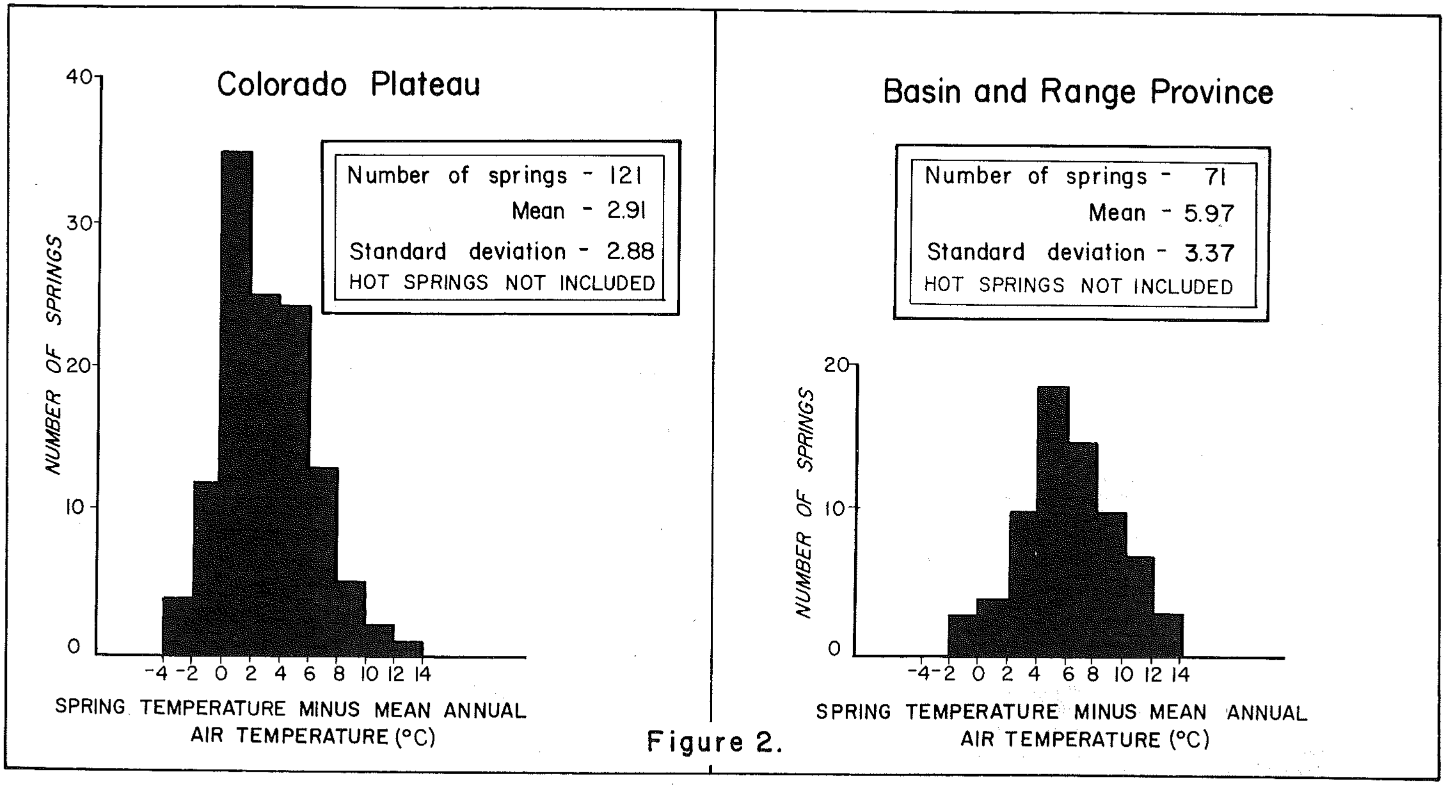

Figure 2.

The normal flow of heat from the earth's interior is probably the major source of heat for Arizona's thermal springs. The earth's internal heat flows or is conducted through rock toward the surface. Subsurface temperatures in Arizona generally increase at least 30°C for every kilometer of depth; therefore, water circulating deeper than 300 meters for a period of time will be heated by subsurface rocks a minimum of 10°C above the MAT. Provided little loss of heat occurs on the way back to the surface, these circulating waters will discharge as thermal springs.

The detailed mechanics and geologic conditions required for deep circulation of water are beyond the scope of this article. However, it is believed that forced convection accounts for Arizona's thermal springs because the vertical permeabilities in fault zones and Arizona's subsurface temperature gradients are too low for free convection. Free convection is buoyant flow of water caused by a temperature-induced vertical differential in water density. Forced convection is pressure-induced water flow caused by elevation differences between the recharge water table and the springs discharge elevation. Deep forced convection requires special structures, stratigraphic geometries and geohydrologic conditions.

Studies of Arizona's thermal springs are but a part of the Arizona Bureau of Geology and Mineral Technology's assessment and characterization of Arizona's geothermal resources. The entire study is being funded by the U.S. Department of Energy.

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GEOTHERMAL

On January 16, 1981, the Geothermal Project of the Bureau of Geology and Mineral Technology, Geological Survey Branch, received a one-year contract renewal to continue the low- to moderate-temperature geothermal site evaluation in the state of Arizona during 1981. Funds for this year's program, $274,918.00, again came from the U.S. Department of Energy, Division of Geothermal Energy.

This year is the final year for the program. Work, therefore, will focus on completing the statewide geothermal resource assessment and on closing down the program. All data and reports generated over the lifetime of the program will be indexed and catalogued into a format that is useful and easily accessible to future workers. Everything will be left on file at the Bureau of Geology and Mineral Technology. A final report on the geothermal resource potential of Arizona will be prepared.

Many areas with potential geothermal energy favorable for direct use have been identified in the state. It is hoped that development of these resources will be carried out by the private sector.

Claudia Stone, Geologist with the Bureau since 1977, has been selected Program Manager for the Geothermal Project. Claudia began geothermal study in 1975 when attending the University of Hawaii. She received a M.S. in Geology and Geophysics in Hawaii (1977) and a B.A. in Journalism from Marquette University (1961).

Starting as Research Assistant for the Tucson Geothermal Project, Claudia has developed various geothermal studies in the state, including the Papago Farm investigation. As Program Manager, she will oversee the final phases of the geothermal program in Arizona.

W. Richard Hahman, Sr., Principal Investigator and Program Manager of the Geothermal Project with the Bureau of Geology and Mineral Technology, left the Bureau in May 1981 to be a consultant and Chief Geologist for an energy and mineral company in Santa Fe, New Mexico.

Dick has been with the Bureau since May 1977, investigating and assessing geothermal resources in Arizona, through funds supplied by the U.S. Dept. of Energy and the U.S. Dept. of the Interior.

Hahman graduated with a B.S. in 1960 from American University and a M.S. in geology at West Virginia University (1963). During the last 20 years, he has developed expertise in the exploration of geothermal energy, porphyry copper, molybdenum, massive sulfide, Mississippi and East Tennessee-type deposits. Dick has worked as an independent consulting geologist in Arizona, California, Nevada, Oklahoma and Utah. He has also been employed by Cominco American Inc. (1970–74), North Carolina Division of Mineral Resources (1965–1970), The Bear Creek Mining Co. (1965), Duval Corp. (1964–65) and the Superior Oil Co. (1963–64).

OPEN FILE REPORTS

Open File Reports are being cataloged and indexed by Bureau staff. These reports were prepared by the U.S. Geological Survey, the Department of Energy and the Bureau of Geology and others. They are available for public review.