Reconnaissance Study of the Geothermal Resources of Modoc County, California

by

Wendell A. Duffield and Robert O. Fournier

U. S. Geological Survey

OPEN FILE REPORT

February 1974

This report is preliminary and have not been edited or reviewed for conformity with Geological Survey standards and nomenclature.

Contents

Introduction

The purpose of this report is to evaluate the geothermal resources of Modoc County, Calif. The information used in this evaluation comes primarily from geologic literature previously published by other workers and our own reconnaissance of the field area (2 weeks by Duffield and 4 days by Fournier). Duffield also has relatively detailed knowledge and related background information of the geology of a small part of the county, gained from recently completed fieldwork for a mineral resources evaluation of the South Warner Wilderness in southeast Modoc County.

In view of the size of the county (4,097 mi^2) and the short time available for field examination, most of the fieldwork was concentrated in east and north-central parts of the county--areas that are relatively attractive exploration targets based on the occurrence of hot springs and young volcanic rocks. In general, all of Modoc County is a potentially attractive target for the exploration of geothermal resources, because virtually the entire county is underlain by Miocene or younger volcanic rocks. This suggests the possibility that large amounts of energy may be stored locally in still molten or solidified but still hot, shallow bodies of magma. Several occurrences of hot springs in the east part of the county indicate the presence of shallow elevated temperatures there. Other areas of shallow elevated temperature that are not expressed at the surface by hot springs, geysers, and fumaroles could be present.

Previous work

Considering the ease of accessibility and the favorable degree of bedrock exposure for studying problems in volcanology, surprisingly little geological fieldwork has been done in Modoc County, as confirmed by the index to geologic mapping that accompanies the Alturas sheet (Gay and Aune, 1958) of the geologic map of California. Even today, 15 years later, the only additional published mapping in the County has been that of Ford and others (1963) as part of their study of the major ground water basins in northeastern California.

Hill (1915) published a sketch map of the geology of the High-grade mining district, a small gold district in the north Warner Mountains. Hill's work, however, is of little value in understanding the areal stratigraphy and provides no age data. Russell (1928) mapped the entire Warner range, with emphasis on structure. Relatively recent fieldwork by Hulbe and Emerson (1969), Martz (1968), and Duffield (unpub. data) indicates that Russell's work needs considerable revision, especially his interpretation of formational units and stratigraphy, but none of these recent workers has yet published a map. Thus, except for the work of Ford and others (1963), Hill (1915), and Russell (1928), Modoc County has been mapped only from the study of aerial photographs, with minor field checks, all done by T. E. Gay, Quintin Aune, and C. W. Chesterman (1958) of the California Division of Mines and Geology.

Geologic setting and areas of field study

Modoc County lies in the extreme northeast corner of California, sharing common boundaries with Nevada and Oregon (fig. 1). Most of the county is within the Modoc Plateau geomorphic province, but the Warner Mountains and adjacent Surprise Valley in the eastern part of the county are within the Basin and Range province. The Modoc Plateau is characterized by flat-lying pyroclastic rocks with intercalated basalt flows and, generally, capping basalt flows. The entire section is highly broken by north- to northwest-trending normal faults and is partly dissected so that the plateau ranges from about 5,000 to 6,000 feet in elevation.

The north-trending Warner Mountains and adjacent Surprise Valley are a horst and graben, respectively, of typical Basin and Range structure. From about Fandango Pass southward (see pl. 1) the range is underlain principally by up to 10,000 feet of conformable sedimentary and volcanic rocks, dipping about 25° to the west. North of Fandango Pass the section is tilted gently eastward. At Cedar Pass the normal section is partly replaced by two central volcanoes (Christoph Hulbe, 1972, oral commun.). The crest of the mountains varies from about 6,500 to 8,500 feet in elevation, and reaches a maximum of nearly 10,000 feet at Eagle Peak, near the south end of the range.

Surprise Valley contains up to 7,000 feet of sediments eroded from the adjacent mountains. This valley has internal drainage, and three large shallow alkaline lakes presently cover much of the valley floor; these lakes are ephemeral and may dry up completely after a single year of low precipitation.

Although supporting data are few, all rocks in Modoc County are believed to be Cenozoic in age, mostly Miocene and younger. Nearly all age determinations are based on about 20 fossil localities, scattered widely in the south county part of the Modoc Plateau (Quintin Aune, written commun., 1973). Two radiometric dates have been published. Coe (1967) reported a K-Ar whole rock age of 7.2 m.y. for a flat-lying basalt flow of the Modoc Plateau exposed in a road cut about 4 miles northeast of Alturas on Highway 395. Axelrod (1966) reported a K-Ar age of 40 m.y. on plagioclase from an andesite flow low in the central Warner Mountains section. The interpretation of such single, isolated radiometric dates is often difficult, but in those two instances the numbers are consistent with all fossil evidence and should probably be accepted at face value.

Several K-Ar ages have been determined for rocks of the South Warner Wilderness, and indicate that the section there ranges from at least 32-15 m.y. old. Thus, all available evidence suggests that the oldest rocks in the county are lower Oligocene and exposed at the base of the Warner Mountains section, whereas the youngest rocks probably are Plio-Pleistocene basalt flows of the Modoc Plateau. However, there are large areas of bedrock whose age is only indirectly inferred and, clearly, future work may modify this generalization.

Field study for this report was concentrated in Surprise Valley and adjacent parts of the Warner Mountains, the Devils Garden, and along the Likely fault zone (pl. 1). Surprise Valley was selected because of the abundance of hot springs there; the Devils Garden because of the abundance of perhaps the youngest lava flows in the county; and the Likely fault zone because a hot spring is located near its trace at Canby and because this fault zone is part of a major structural trend also expressed in the first two areas.

Results of present field investigation

Likely fault zone

The Likely fault zone was briefly examined along logging roads that crisscross the trace of the fault. Gay (1959) attributes major lateral offset to the fault, but there appears to be no definitive evidence of such offset in Gay's mapping (1959; Gay and Aune, 1958), and the present field study uncovered no evidence suggesting sense of fault motion. The rocks on both sides of the fault zone are mostly flat-lying basalt flows of questionable age and as such are poor markers of relative offset. Detailed petrographic, chemical, or radiometric age studies might establish the sense of fault offset, but until these or other definitive studies are done, this offset should be considered unknown. Comparison with parallel structural trends to the north, as discussed later, suggests the possibility of primarily tensional opening and associated vertical offsets along the fault.

The well-known Kelley hot spring is located just east of the Likely fault zone, near Canby (pl. 1). This spring was examined and drilled by private industry in 1969 (table 1), but apparently was not considered worthwhile for any additional development. No other hot springs or evidence of recent hot-springs activity were discovered along the fault zone during the present study. However, the Likely fault zone should still be considered a potential target for geothermal exploration, especially in view of the possible similarities between this and the two more northerly parallel structural zones, discussed later.

Devils Garden

The geology of the Devils Garden area (pl. 1) was reconnoitered along many tens of miles of logging roads. Most of the area is underlain by flat-lying basalt flows that are broken by north- to northwest-trending normal faults. At the south edge of the area, about 6 miles west-northwest of Alturas, fossils of Blancan age have been recovered from strata just beneath the basalt, indicating a Plio-Pleistocene or younger age for the flows (Quintin Aune, written commun., 1973). At the north edge of the area, along and near the Oregon border, these flows lap onto slightly southward tilted older (Pliocene or Miocene?) basalt.

Table 1. *Geothermal wells in Modoc County*

Well	Location	Depth in feet	Year drilled	Bottom Hole Temperature °C	Time between temperature measurement and last circulation of drilling mud	Driller
Kelly Hot Spring 1	Sec. 29, T. 42 N., R. 10 E.	3,206	1969	110	24 hours	Geothermal Resources International
Parman 1	Sec. 24, T. 44 N., R. 15 E.	2,150	1959	140	^ 1 year	Magma Energy, Inc.
Parman 2	Sec. 24, T. 44 N., R. 15 E.	1,968	1959	>125	Flow line temperature	Magma Energy, Inc.
Parman 3	Sec. 24, T. 44 N., R. 15 E.	92	1962*		---	Magma Energy, Inc.
Phipps 1	Sec. 24, T. 44 N., R. 15 E.	1,267	1962	137	64 hours	Magma Energy, Inc.
Cedarville 1	Sec. 6, T. 42 N., R. 17 E.	734	1962	54	15 hours	Magma Energy, Inc.
Phipps 2	Sec. 24, T. 44 N., R. 15 E.	~4,500	1972	~160° at about 3800'	?	Magma Energy, Inc.
Surprise Valley 1ST	Sec. 30, T. 44 N., R. 16 E.	~7,000	1973	?	---	Gulf Oil
Surprise Valley 2ST	Sec. 13, T. 43 N., R. 16 E.	~6,500	1973	?	---	Gulf Oil

*Drilling was immediately adjacent to the site of the 1951 mud volcano eruption. Drilling stopped when the rig fell into a small mud crater caused by a minor steam blowout.

Locally, small cinder cones and two larger (up to 2 miles in diameter) lava shields rise above surrounding flows. These central vents probably served as feeders for at least some of the flows. The shields lie along and partly define an inferred fault zone-volcano lineament that slices across the entire county in a northwest direction, virtually parallel to the Likely fault zone (see pl. 1). From northwest to southeast this inferred structure includes the northwest-trending faults north of Carr Butte along the north-central boundary of the Alturas sheet (Gay and Aune, 1958), trends through Blue and Round Mountains of the Devils Garden, slices across the Warner Mountains obliquely at Cedar Pass, the locus of two major volcanoes, and projects across the southern termination of a bedrock fault block buried beneath recent sediments in Surprise Valley to the center of the Hays Canyon Volcano on the east side of Surprise Valley in Nevada.

If this inferred structure is in fact real, it apparently has served repeatedly as a conduit for rising magma, as recently as Plio-Pleistocene or younger time. If so, it must then be considered an attractive target for geothermal exploration in the Devils Garden area, and perhaps elsewhere along strike, too. Interestingly, the only known occurrence of rhyolite and associated obsidian in the Devils Garden area crops out along the lineament adjacent to Blue Mountain on the west, suggesting the possibility of a shallow rhyolitic magma chamber. However, the age of this rhyolite and the significance of the inferred lineament are both speculative and any exploration program should be tempered accordingly. Nonetheless, presently available data suggest that basalt flows of Devils Garden are the youngest volcanic rocks in Modoc County, and this fact alone makes the area an attractive target for possible further investigation.

Surprise Valley and the Warner Mountains

Surprise Valley has long been an area of well-known hot springs activity. It was the site of a violent mud volcano eruption in 1951 (White, 1955) and was recently classified as a "known geothermal resources area" (Godwin and others, 1971). There are eight subareas of hot springs activity in the valley, six of which are in the north half (pl. 1). Rates of flow and maximum water temperatures vary considerably from area to area; these and other data are compiled in table 2.

Table 2. *Hot Springs of Surprise Valley*

Springs	Corre-sponding sample no. in table 3	Location	Maximum T., °C	Visually estimated flow rate, in 10's of gal/min	Comments
Fort Bidwell (2 springs)					
A	SVF 24	NE1/4, sec. 17 T. 46 N., R. 16 E.	46	A few to several	Flow is through corroded well-casing pipe.
B	SVF 23	Sec. 8, T. 46 N., R. 16 E.	43	A few	Water used domestically.
Lake City Mud Volcano		Secs. 23 and 24, T.44 N., R. 15 E.			See tables 1 and 3.
Nameless cluster of several small springs	SVF 29	Near common corner of secs. 1, 2, 11, 12, T. 43 N., R. 16 E.	87	A few	
Boyd	SVF 34	Sec. 31, T. 45 N., R. 17 E.	20	Several	Shown as hot spring on topographic map but is actually a cool spring.
Leonard (2 springs)					
A	SVF 31 and SVF 32	At common corner of secs. 7, 12, 13, 18, T. 43 N., R. 16 and 17 E.	66	Several	Located about 1/2 mile NNE of old Leonard Spa bathhouse.
B	SVF 30	Sec. 13, T. 43 N., R. 16 E.	41	Several	Located at bathhouse area.
Surprise Valley Mineral Wells or Cedarville Plunge (4 groups of springs)[1]					
A	SVF 4	Near center of sec. 6, T. 42 N., R. 17 E.	[2] 87	Several	Flow is from two wells at the Lodge. The water is used in a swimming pool and to heat the lodge in winter.
B		Sec. 6, T. 42 N., R. 17 E.	[2] 93	Many	Flow is from a cluster of four springs, near an old barn about 1/4 mile east of the Lodge.
C	SVF 5 and SVF 7	SW1/4 sec. 6, T. 42 N., R. 17 E.	98	Many	Flow is from 2 springs about 1/3 mile southwest of Lodge.
D	SVF 6	SE1/4 sec. 1, T. 42 N., R. 16 E.	[2] 93	Several to many	At abandoned shack about 1/2 mile southwest of lodge.
Menlo Baths (2 groups of springs)					
A	SVF 1	NE1/4 sec. 7, T. 39 N., R. 17 E.	59	Several	Nearby warm water well used as domestic water supply and heating. Water from both areas is collected in cooling ponds and then used for irrigation. (A and B)
B		SE1/4 sec. 6, T. 39 N., R. 17 E.	53	A few	Flow comes from several small seeps in hillside.
Squaw Baths (group of three springs)					
A	SVF 2	NE1/4 sec. 29, T. 39 N., R. 17 E.	43	A few	The three springs are within 300 feet of one another aligned approximately south-north (C+A) in the road ditch of Surprise Valley Highway.
B	SVF 2	NE1/4 sec. 29, T. 39 N., R. 17 E.	42	Several	
C	SVF 2	NE1/4 sec. 29, T. 39 N., R. 17 E.	35	A few	

[1] Water is boiling at all springs.

[2] Temperatures where thermometers could not be submerged directly in the throat of a spring—probably a few degrees too low. Flow rates may be estimated from the following scale: Few = up to 4; Several = 4 to 8; Many = 8 to 16. Many springs showed some evidence of carbonate deposition and a few showed minor SiO_2 deposition.

Geologically, Surprise Valley is a north-trending graben sandwiched between the Warner Mountains and the Hays Canyon Range, adjacent horsts on the west and east, respectively. The Surprise Valley fault zone, the range front fault zone on the west side of the valley, has undergone at least 5,000 feet vertical offset, and possibly as much as 11,000 feet. Radiometric age data from rocks in the south end of the Warner Mountains, suggest that this faulting began no longer than 15 m.y. ago, and scarps in alluvium along the present range front indicate some recent motion. The amount and timing of faulting along the east edge of Surprise Valley have not been established but must be similar to those along the west.

Some faults within Surprise Valley have been mapped by geologists of the California Division of Mines and Geology on the Alturas sheet (Gay and Aune, 1958), and by Ford and others (1963). Some are indicated by exposures of bedrock, but many have been inferred from detailed gravity surveys by Ford and others (1963). Most of these faults trend either north or northwest.

The Warner Mountains horst has been tilted westward south of the area of Fandango Pass, and eastward north of this area (pl. 1). Fandango Pass is along the northwest-trending Fandango fault zone, and in addition to marking the point of reversal in tilt of the Warner Range, it also is an area of abundant rhyolite and associated obsidian. Furthermore, the Fandango fault zone parallels the Likely fault zone and the inferred lineament described earlier, and projects to parallel faults across Goose Lake to the northwest and across Surprise Valley to the southeast. The sense of motion along the Fandango fault zone is speculative, but Fandango Valley within the fault zone probably is a graben, suggesting vertical and possibly associated extensional movement. The fault zone is a few miles wide (Gay and Aune, 1958), and appears to have localized rhyolite flows and associated fresh obsidian (both mapped as Tertiary intrusive by Gay and Aune, 1958). These rhyolite-obsidian bodies possibly are of special significance to our study because of the common association of such rocks with hot springs areas. The only other such rocks known in the Warner Mountains crop out near the south end of the range (see pl. 1).

Based on the above geologic data, there appear to be three direct correlations of decreasing perfection between the hot springs of Surprise Valley and associated geology.

1. Without exception, the hot springs are structurally controlled. Many of them are localized along the Surprise Valley fault zone. The others are along faults mostly mapped by Ford and others (1963) from detailed gravity data on the valley floor. The range front fault zone is clearly a major structure with thousands of feet of vertical offset. The other faults probably have undergone less offset, but, nonetheless some are traceable for 13 miles beneath alluvium by gravity measurements (Ford and others, 1963).

2. With the possible exception of Surprise Valley Mineral Wells (sometimes called the Cedarville Plunge) hot springs area, all hot springs are no farther than 3 miles from rhyolite flows and (or) plugs. Surprise Valley Mineral Wells may also be near rhyolite, but if so, the rock is buried beneath the alluvial valley fill that surrounds the area for several miles. Hot springs and rhyolite are absent along the central 25 miles of the Surprise Valley fault zone and adjacent Warner Mountains.

3. The greatest number of hot springs, representing the hottest surface water temperatures and the bulk of outflow of hot water, are associated with the area of the most voluminous and youngest looking rhyolite-obsidian bodies, which occur in the north half of the Surprise Valley-Warner Mountains area as distinguished from the south end. If the surface rhyolite rocks indicate the presence of underlying shallow rhyolitic magma that provides heat for the hot springs, a relation that seems established for some geothermal areas elsewhere, and if relatively older and therefore cooler magma gives rise to cooler springs, then the suggestion has some merit. Attempts to date some of the rhyolite-obsidian bodies radiometrically are now in process. Maximum subsurface water temperatures estimated from the chemistry of the thermal waters are consistent with the above proposal (see table 3).

We sampled 14 hot springs and 19 nearby cold wells and springs in Surprise Valley for chemical analyses. Based on water chemistry, most of the hot springs appear to be mixtures of deep, hotter water and shallow cold water. Unfortunately, the composition of the shallow cold water varies from very dilute to very saline, owing to varying amounts of mixing of regular ground water with alkali lake water and, possibly, solution of old evaporite deposits. This makes interpretation of the hot-spring compositions very difficult and subsurface temperature estimates suspect. With this difficulty in mind various geochemical techniques were used to estimate subsurface temperatures at the five main hot-spring localities in Surprise Valley. The results are summarized in table 3.

Table 3. *Chemical analyses, physical data, and subsurface temperatures estimated by various geochemical techniques at selected hot spring localities in Surprise Valley, California. Anion analyses by J. M. Thompson and cation analyses by T. Presser. All analytical values expressed as parts per million*

Location	Sample No.	Estimated flow rate liters/min.	Well depth meters	Temp. °C	SiO_2	Li	Na	K	Mg	Ca	HCO_3	SO_4	Cl	F	B	Quartz[7] est. t	Na-K-Ca[8] est. t	Mixing models a[9]	Mixing models b[10]	Mixing models c[11]
South of Eagleville																				
NE¼NE¼ sec. 7, T. 39 N., R. 17 E.	SVF 1 Spring	[1]150-200		59	56.6	0.03	98	1.43	0.08	6.0	82.6	120	25.5			105	61	126	116	
NE¼ sec. 29, T. 39 N., R. 17 E.	SVF 2 Spring	[1]150-200		41	39.8	<.01	61.5	1.12	<.05	2.4	85.7	41	14.1							
	SVF 3 Spring	[1]100-150		11	37.7	<.01	4.0	3.07	4.4	9.3	62.4	0.6	<10							
SW¼NW¼ sec. 18, T. 40 N., R. 17 E.	SVF 26 Well[2]	?		Cold	44.9	.01	19.5	4.87	6.9	20.3		3.2	.55							
SW¼NW¼ sec. 19, T. 40 N., R. 17 E.	SVF 27 Well[3]	>2,000		Cold	40.9	.01	22	3.25	4.9	18.7		13	3.9							
	SVF 28 Well[4]	15-20		12	59.1	<.01	44	6.7	8.0	32.8		65	26.2							
Mineral Wells Hot Springs																				
NE¼SW¼ sec. 6, T. 42 N., R. 17 E.	SVF 4 Well	100-175		98 (Boiling)	105	.08	297	6.0	<.05	17	69.4	310	198	5.4	5.9	135	116			142
SW¼SW¼ sec. 6, T. 42 N., R. 17 E.	SVF 5 Spring	600-800		96	99.6	.09	285	6.0	.05	18	72.7	310	188	5.0	5.6	132	117			
SE¼SE¼ sec. 1, T. 42 N., R. 16 E.	SVF 6 Spring	500-700		Boiling	98.7	.07	285	6.0	.05	15	59.8	310	186	5.0	5.7	135	118			
SW¼SW¼ sec. 6, T. 42 N., R. 17 E.	SVF 7 Spring			81	105	.08	277	6.0	.05	17	60.1	290	192	5.0	5.6	140	118			148
	SVF 8 Well[5]	Large		17	73.5	<.01	750	7.3	.08	1.55	274	340	594	5.8	9.2					
Leonard Hot Springs																				
NW¼NW¼ sec. 12, T. 43 N., R. 16 E.	SVF 29 Spring	20-40		86	114	.15	342	9.7	.29	31	74.4	380	213	5.1	7.4	144	130	183	152	
NW¼NE¼ sec. 13, T. 43 N., R. 16 E.	SVF 30 Spring	[1]175-225		41	58.4	.10	403	5.7	3.45	15	182	400	218	4.4	7.6	108	107	152	135	
Common corner at secs. 12, 13 and	SVF 31 Spring	200-300		60	113	.15	343	9.0	.61	27	90.2	390	213	5.0	7.5	144	119	225	170	
7, 18, T. 43 N., R. 16 and 17 E.	SVF 32 Spring	30-50		65	117	.15	340	8.0	.42	28	88.5	—	211	5.0	7.6	146	121	220	167	
NW¼NW¼ sec. 20, T. 43 N., R. 17 E.	SVF 33 Well[6]	Intermittent		?	50.9	.01	128	2.9	1.1	7.0	204	64	52.4	.9	.9					
Boyd Spring																				
SW¼NW¼ sec. 31, T. 45 N., R. 17 E.	SVF 34 Spring			19																
Mud Volcano Area																				
NW¼SE¼ sec. 24, T. 44 N., R. 15 E.	SVF 9 Spring	2-4		86	182	.23	343	16.3	.05	11	124	330	223	6.8	6.4	174	160			
NW¼SE¼ sec. 24, T. 44 N., R. 15 E.	SVF 10 Spring	Small		89	176	.26	335	16.5	.24	26	185	330	222	6.5	6.2	172	153			
NW¼NW¼ sec. 32, T. 44 N., R. 16 E.	SVF 11 Well[2]	Small		13.5	44.4	<.01	25.0	3.95	5.2	12	141	15	.40							
SE¼NE¼ sec. 32, T. 44 N., R. 16 E.	SVF 12 Well[2]	Small	35.7	15.5	47.8	<.01	26.5	3.73	4.7	13	135	6.1	.85							
NE¼SE¼ sec. 32, T. 44 N., R. 16 E.	SVF 13 Well[2]	Small	18.3	?	47.7	<.01	16.0	2.63	6.6	18	138	5.0	.70							
NE¼SE¼ sec. 32, T. 44 N., R. 16 E.	SVF 14 Well[2]	Small		11	58.5	<.01	24.3	3.65	4.3	15	131	3.8	.80							
NE¼SE¼ sec. 32, T. 44 N., R. 16 E.	SVF 15 Well[2]	Small	36.6	11	47.5	<.01	16.5	2.40	6.6	18	131	4.5	.75							
SW¼SW¼ sec. 29, T. 44 N., R. 16 E.	SVF 16 Well[2]	Small		?	45.0	<.01	80	2.03	.44	1.35	208	1.4	.90							
NE¼NE¼ sec. 36, T. 44 N., R. 15 E.	SVF 17 Well[2]	<3		11	38.0	<.01	9.5	1.55	8.4	19	129	3.0	.70							
NW¼SW¼ sec. 13, T. 44 N., R. 15 E.	SVF 18 Well[2]	Small	19.8	?	35.9	<.01	10.0	3.15	10.5	21	142	3.8	.75							
Fort Bidwell																				
SW¼SE¼ sec. 30, T. 46 N., R. 22 E.	SVF 19 Well[2]	Small		13.5	48.4	<.01	20	1.50	8.3	16.5	142	3.2	1.0							
SW¼NE¼ sec. 29, T. 46 N., R. 22 E.	SVF 20 Well[4]	Small		12	52.1	<.01	138	1.86	.24	.8	297	7.9	24.4							
NW¼NE¼ sec. 29, T. 46 N., R. 22 E.	SVF 21 Well[4]	Small		10	45.8	<.01	247	2.13	.17	.8	513	12	29.6							
NW¼NE¼ sec. 20, T. 46 N., R. 22 E.	SVF 22 Well[3]	8,300		14.5	66.6	<.01	61.5	6.7	5.2	10.5	155	44	16.2		.3					
SE¼NW¼ sec. 8, T. 46 N., R. 22 E.	SVF 23 Spring	[1]75-80		43	77	.01	80	7.2	2.1	4.7	135	58	25.4		.8		122	173	185	147
NW¼NE¼ sec. 17, T. 46 N., R. 22 E.	SVF 24 Well	175-225		45	94.4	.04	110	10	.13	5.0	141	89	33.1		.7	133	180	220	169	
	SVF 25 Well[2]	Small	36.6	Cold	49.9	<.01	97	2.58	.17	2.8	222	19	16.1		.3					

[1]Total flow from the area.

[2]Domestic water supply for private residence.

[3]Irrigation water supply.

[4]Artesian flow to supply water to livestock.

[5]Domestic supply for Hot Springs Motel.

[6]Wind-powered pump.

[7]The silica geothermometer of Fournier and Rowe (1966).

[8]The Na-K-Ca geothermometer of Fournier and Truesdell (1973).

[9]Mixing model 1 of Fournier and Truesdell (1974a).

[10]Mixing model 2 of Fournier and Truesdell (1974b).

[11]Mixing model assuming the chloride concentration in the deep water component is 223 ppm and the shallow component contains 50 ppm chloride. Temperatures are obtained from adjusted silica concentrations.

The least diluted samples of deep, hot water probably were found in the two hot springs at the Lake City area, samples SVF 9 and 10. The silica in those samples suggests a subsurface temperature of last equilibration with quartz of 172°-174°C. The depth of last equilibration is not known, but under the best of conditions it is unlikely that hot-spring-water composition will give reliable information about subsurface temperatures deeper than 3,000-4,000 feet owing to increased likelihood of reaction with wallrock during flow to the surface. Thus, the measured temperature of about 160°C at 3,828 feet in the nearby Phipps 2 drill hole is considered to be in excellent agreement with the subsurface temperature estimated from the composition of the spring water.

The temperature of the aquifer supplying water to the springs at Surprise Valley Mineral Wells hot springs probably is 135°-145°C. Subsurface temperatures at both Leonard Hot Springs and Fort Bidwell probably are in the 170°-185°C range. In contrast, subsurface temperatures south of Eagleville probably are below 100°C, with the best guess at 60°±15°C.

Marshall Reed, of the California Division of Oil and Gas, is also studying water chemistry of some Surprise Valley ground water, but the authors do not yet know the results of his study.

Private industry has shown some interest in the geothermal resources of Surprise Valley for several years. Actual development by private industry includes eight drill holes ranging in depth from about 90 to 7,000 feet. Additional information about the drill holes is shown in table 1.

Conclusions

Even though Modoc County is largely underlain by mid to late Cenozoic lavas, direct surface evidence of anomalous shallow concentrations of geothermal energy is not particularly abundant. Geothermal resources, of course, need not be expressed as directly observable phenomena such as hot springs, but a realistic approach to further exploration in Modoc County would probably favor additional studies of geology, water chemistry, and perhaps geophysics in the obviously hot areas before possible studies elsewhere. If one accepts this approach to the problem, then Surprise Valley and adjacent area is the prime target for further exploration.

The presently known geothermal resource in Surprise Valley probably could be developed commercially. The question to which there is as yet no well-established answer is: to what degree could exploration and development proceed and remain a profitable venture? The chemistry of the waters suggests that maximum expectable temperature at shallow depth is not particularly hot, a conclusion that generally has been borne out by measurements in the few existing drill holes. Thus, it would appear that Surprise Valley may not become a large producer of geothermal energy for exportation outside the valley, at least given the present state of technology.

However, there are adequate hot springs with sufficient rate of flow, especially in the northern end of Surprise Valley, to consider use of the water for space heating and raising crops during the winter. A few buildings already are heated with the naturally hot waters (see table 2). Winter crop raising might be run at a fairly large scale. There is plenty of fertile land on the west side of the valley, where most of the hot springs are located. The natural flow rate of hot springs could almost certainly be supplemented greatly by shallow wells drilled near existing hot springs. Locally, this has already been done to some degree, as many people near hot springs have drilled unsuccessfully for cold water wells. At present, virtually all the thermal waters and the land are unused during the winter months.

But whether an agricultural project could be promoted or not, we recommend the Surprise Valley area, especially the northern half, as a possible target for additional study. Geologic mapping in the north Warner Mountains, where rhyolite and obsidian are known but have only been mapped in reconnaissance by Russell (1928), together with appropriate geophysical surveys in the mountains and adjacent parts of the valley, would almost certainly help define the extent and character of the geothermal resource there to a much greater degree than can be surmised from scanty knowledge presently available. To date, the presence of the rhyolitic rocks and their possible relation to the geothermal resources in Surprise Valley apparently have been completely ignored. Relatively little fieldwork would be required to test the possible geothermal-related significance of these rocks.

Selected references

Avent, J. C., 1971, Chemical correlation of the Mesa and Warner basalts by the fusion method: Geol. Soc. America, Abstracts with Programs, v. 3, no. 2, p. 76.

Axelrod, D. I., 1966, Potassium-argon ages of some western Tertiary floras: Am. Jour. Sci., v. 264, p. 497-506.

Chapman, R. H., and Bishop, C. C., 1968, Bouguer gravity map of California, Alturas sheet: California Div. Mines and Geology, scale 1:250,000.

Coe, R. S., 1967, Paleo-intensities of the earth's magnetic field determined from Tertiary and Quaternary rocks: Jour. Geophys. Research, v. 72, p. 3247-3262.

Evernden, J. F., and James, G. T., 1964, Potassium-argon dates and the Tertiary floras of North America: Am. Jour. Sci., v. 265, p. 945-974.

Evernden, J. F., Savage, D. E., Curtis, G. H., and James, G. T., 1964, Potassium-argon dates and the Cenozoic mammalian chronology of North America: Am. Jour. Sci., v. 262, p. 145-198.

Ford, R. S., Soderstrand, J. N., Franson, R. E., Beach, F. H., Feingold, S. A., Hail, W. R., Iwamura, T. I., and Swanson, A. A., 1963, Northeastern counties ground-water investigation: California Water Resources Bull. 98 (includes two volumes and three appendices, all bound separately).

Fournier, R. O., and Rowe, J. J., 1966, Estimation of underground temperatures from the silica content of water from hot springs and wet-stream wells: Am. Jour. Sci., v. 264, p. 685-697.

Fournier, R. O., and Truesdell, A. H., 1973, An empirical Na-K-Ca geothermometer for natural waters: Geochim. et Cosmochim. Acta, v. 37, p. 1255-1275.

_____ 1974a, Geochemical indicators of subsurface temperature. Part I, Basic assumptions: U.S. Geol. Survey Jour. Research, v. 2, no. 3 (In press).

_____ 1974b, Geochemical indicators of subsurface temperature. Part II, Estimation of temperature and fraction of hot water mixed with cold water: U.S. Geol. Survey Jour. Research, v. 2, no. 3 (In press).

Gay, T. E., 1959, Geology of northeastern California: California Div. Mines and Geology Mineral Inf. Service, v. 12, no. 6, p. 1-7.

Gay, T. E., and Aune, Q. A., compilers, 1958, Geologic map of California, Olaf P. Jenkins edition, Alturas sheet: California Div. Mines, scale 1:250,000.

Godwin, L. H., Haigler, L. B., Rioux, R. L., White, D. E., Muffler, L. J. P., and Wayland, R. G., 1971, Classification of public lands valuable for geothermal steam and associated geothermal resources: U.S. Geol. Survey Circ. 647, 18 p.

Hill, J. M., 1915, Some mining districts in northeastern California and northwestern Nevada: U.S. Geol. Survey Bull. 594, 200 p.

Hulbe, C. W. H., and Emerson, D. O., 1969, Volcanic sequence of the Warner Mountains, northern California: Geol. Soc. America, Abstracts with Programs, pt. 3, p. 28.

Kuno, Hisashi, 1965, Fractionation trends of basalt magmas in lava flows: Jour. Petrology, v. 6, no. 2, p. 302-321.

Martz, P. W., 1968, The geology of a portion of the northern Warner Mountains, Modoc County, California: California Univ., Davis, Master's thesis.

McNitt, J. R., 1963, Exploration and development of geothermal power in California: California Div. Mines and Geology Spec. Rept. 75, 44 p.

Russell, R. J., 1927, The land forms of Surprise Valley, northwestern great basin: California Univ. Pub. in Geography, v. 2, no. 11, p. 323-358.

_____ 1928, Basin range structure and stratigraphy of the Warner Range, northeastern California: California Univ. Dept. Geol. Sci. Bull., v. 17, no. 11, p. 387-496.

Walker, G. W., and Swanson, D. A., 1969, Discussion of paper by H. E. Wheeler and H. A. Coombs, "Late Cenozoic Mesa Basalt sheet in northwestern United States": Bull. Volcanol., v. 32, p. 581-582.

Waring, G. A., 1965, Thermal springs of the United States and other countries of the world--a summary: U.S. Geol. Survey Prof. Paper 492, 383 p.

Wheeler, H. E., and Coombs, H. A., 1967, Late Cenozoic Mesa basalt sheet in northwestern United States: Bull. Volcanol., v. 31, p. 21-44.

White, D. E., 1955, Violent mud-volcano eruption of Lake City hot springs, northeastern California: Geol. Soc. America Bull., v. 66, p. 1109-1130.

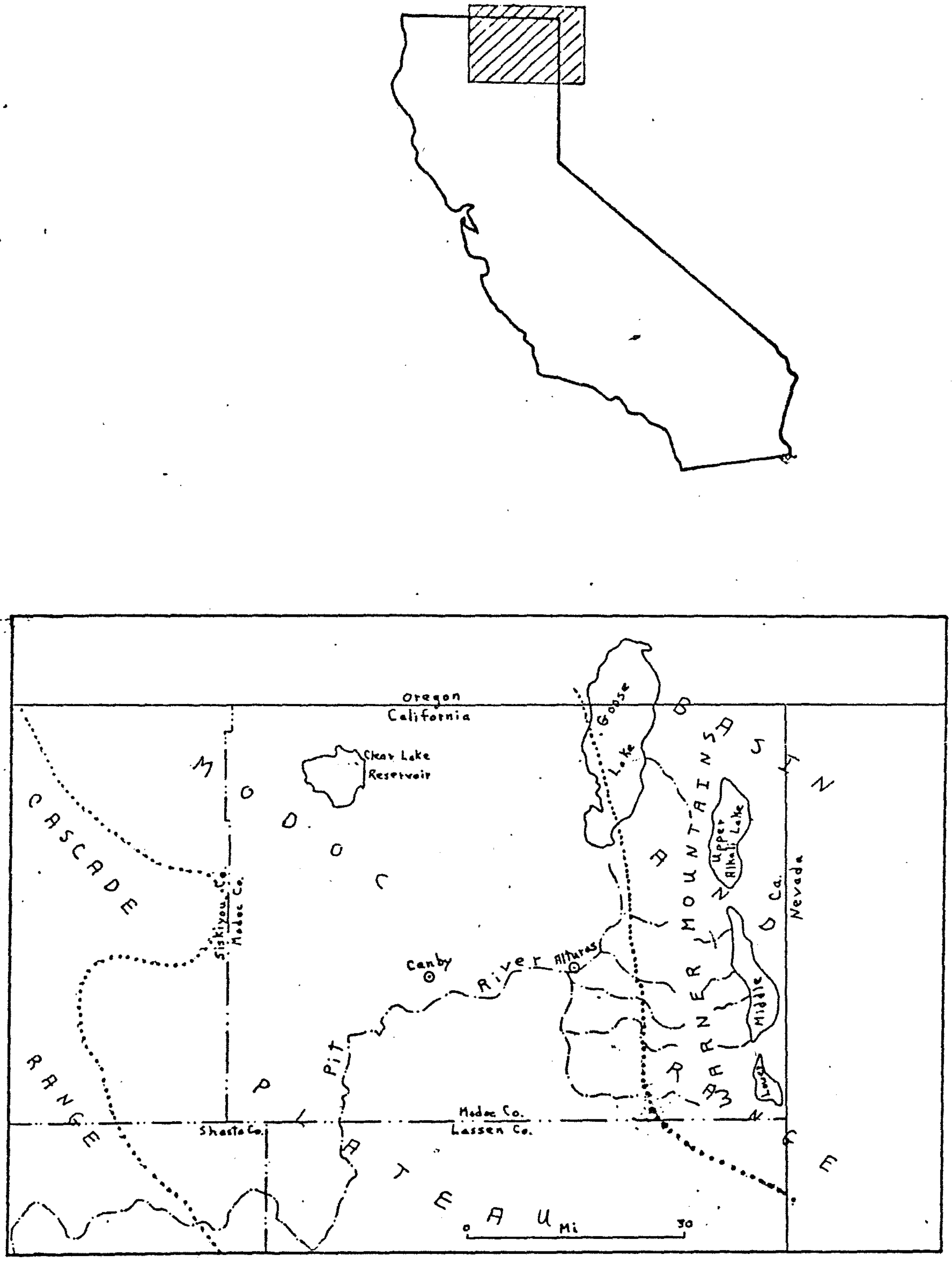

Figure 1. Index map of Modoc County. The dotted lines are boundaries between geologic provinces.

EXPLANATION FOR PLATE 1

Fault or fault zone, dashed and queried where uncertain

Lineament, see text for discussion

Concealed fault, mostly inferred from gravity data

Rhyolite-obsidian

Hot spring locality

Mafic volcanic center

Notes: All known or inferred faults in Surprise Valley are shown (as mapped by Ford and others (1963) and compiled by Gay and Aune (1958)), but to the west only the major northwest-trending fault zones and inferred lineament are shown. The Fandango fault zone is as much as a few miles wide across the Warner Mountains

Other rhyolite-obsidian bodies may occur in the north part of the Warner Mountains, but most of the area has not been field checked