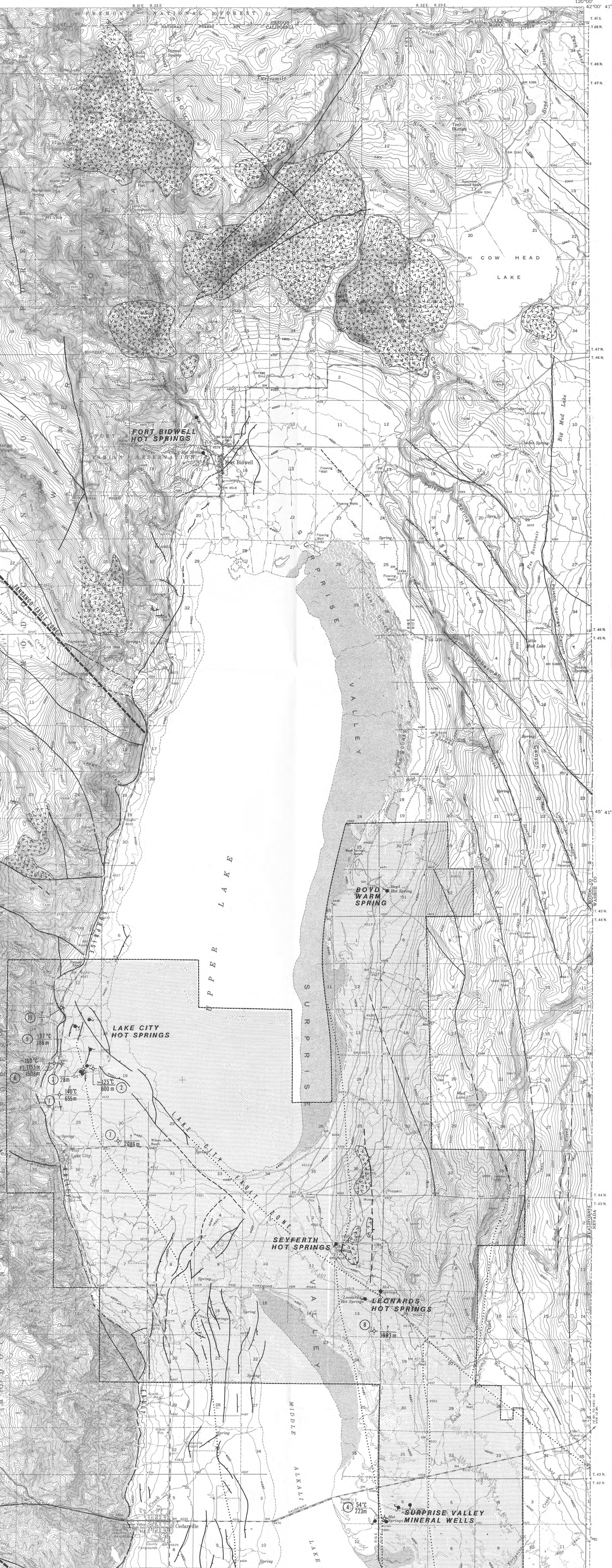
DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

MISCELLANEOUS FIELD STUDIES
MAP MF-1299



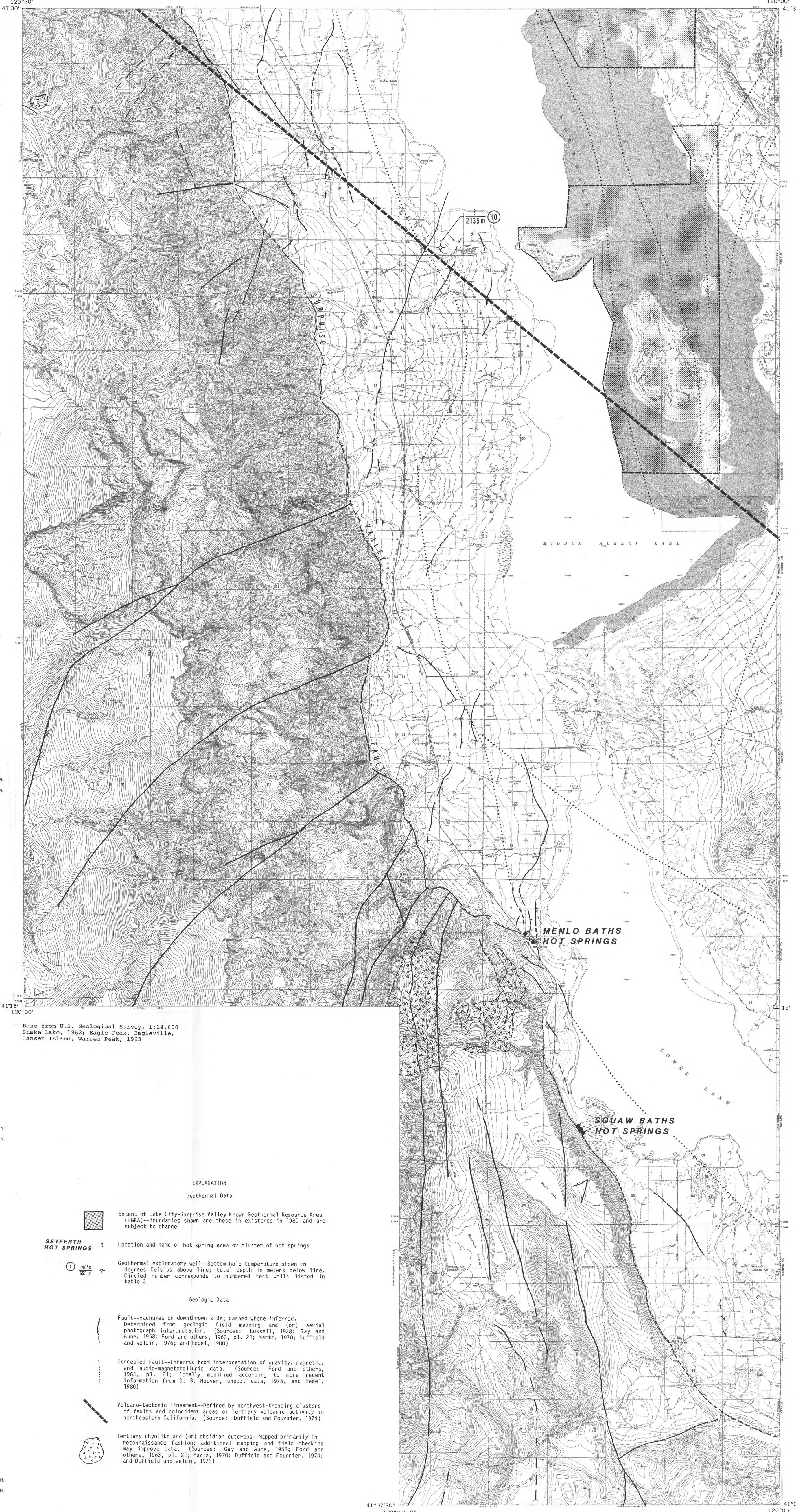
Base from U.S. Geological Survey Cedarville, Fort Bidwell, 1962

SCALE 1:62 500

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Compiled in 1980; aerial-photograph interpretation and field mapping in 1978-79.

NORTHERN PORTION

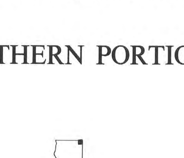


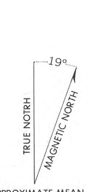
Base from U.S. Geological Survey, 1:24,000
Snake Lake, 1962; Eagle Peak, Eagleville,
Hansen Island, Warren Peak, 1963

SCALE 1:62 500

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

SOUTHERN PORTION





EXPLANATION

Geothermal Data

Extent of Lake City-Surprise Valley Known Geothermal Resource Area (KGRA)--Boundaries shown are those in existence in 1980 and are subject to change

SEYFERTH HOT SPRINGS — Location and name of hot spring area or cluster of hot springs

① 140°C / 655 m — Geothermal exploratory well--Bottom hole temperature shown in degrees Celsius above line; total depth in meters below line. Circled number corresponds to numbered test wells listed in table 3

Geologic Data

Fault--Hachures on downthrown side; dashed where inferred. Determined from geologic field mapping and (or) aerial photograph interpretation. (Sources: Russell, 1928; Gay and Aune, 1958; Ford and others, 1963, pl. 21; Martz, 1970; Duffield and Weldin, 1976; and Hedel, 1980)

Concealed fault--Inferred from interpretation of gravity, magnetic, and audio-magnetotelluric data. (Source: Ford and others, 1963, pl. 21; locally modified according to more recent information from D. B. Hoover, unpub. data, 1975, and Hedel, 1980)

Volcano-tectonic lineament--Defined by northwest-trending clusters of faults and coincident areas of Tertiary volcanic activity in northeastern California. (Source: Duffield and Fournier, 1974)

Tertiary rhyolite and (or) obsidian outcrops--Mapped primarily in reconnaissance fashion; additional mapping and field checking may improve data. (Sources: Gay and Aune, 1958; Ford and others, 1963, pl. 21; Martz, 1970; Duffield and Fournier, 1974; and Duffield and Weldin, 1976)

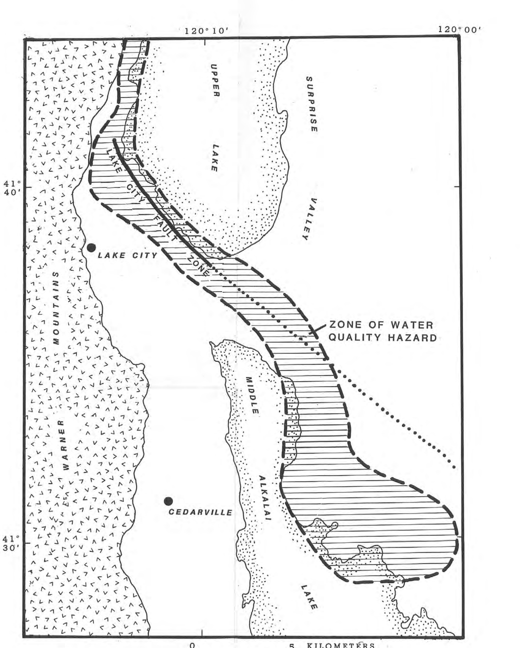


Figure 1--Area of hazardous groundwater (lined area) that is defined by high concentrations of boron, fluoride, sodium, and sulfate. Note close association with Lake City fault zone (from Ford and others, 1963, pl. 23).

INTRODUCTION

This report summarizes geothermal data from published and unpublished geophysical, geochemical, and geologic reports on Surprise Valley that have been prepared during the past 26 years. Particular emphasis is placed on a comprehensive structural interpretation of the west half of the valley that is based on map compilation of concealed faults that have been inferred from geophysical methods and exposed faults that can be seen in the field and (or) on aerial photographs. The faults apparently control the location of modern geothermal activity and are thus important to geothermal exploration.

HISTORY

Geothermal activity in Surprise Valley has long been known. Archeologists have found that the first known human inhabitants of the valley constructed dwellings selectively in hot spring areas 5000 to 6000 years ago (O'Connell and Ericson, 1974). In the early 1900's, spas flourished at Leonards Hot Springs, Menlo Baths, and Surprise Valley Mineral Wells (sometimes called Cedar Plunge), and the operators claimed therapeutic benefits to those who bathed in pools filled with mineralized water from thermal springs. However, Surprise Valley was not considered to be an attractive target for geothermal prospecting until 1951 when a spectacular phreatic eruption of mud volcanoes (White, 1955) occurred at an isolated group of hot springs near Lake City. This eruption propelled rocks, clots of mud, steam, and gases upward as much as 1600 m from six vents ranging from 18 m to 61 m in diameter. Immediately after the explosive eruption, springs at the site discharged water at or near boiling temperatures. Subsequent investigations have shown this group of hot springs to be among the most important geothermal resources in Surprise Valley.

In accordance with the provisions of the Federal Geothermal Steam Act of 1970, 150 km^2 (37,160 acres) in the vicinity of Lake City were designated as potentially valuable for the production of geothermal energy and were classified as a "Known Geothermal Resource Area" (KGRA) by the U.S. Geological Survey (Godwin and others, 1971). In 1974, an additional 145 km^2 (35,780 acres) were so classified, bringing the total area of the KGRA to 295 km^2 (72,940 acres).

NATURE OF GEOTHERMAL RESOURCES

The geothermal resources of Surprise Valley consist of hydrothermal convective systems that are dominated by hot water (Brook and others, 1979, p. 46, 62). Such convective systems typically form when permeable rocks are underlain by a heat source at shallow ($\leq$10 km) depth and meteoric water and (or) surface runoff percolate downward toward the heat source. Heating and thermal expansion cause thermal fluid to circulate upward where it may be trapped beneath an impermeable cap rock or escape to the ground surface if open channelways permit. Most known convecting systems are characterized by hot springs and (or) fumaroles that discharge at the ground surface.

Thermal springs occur in eight principal areas in Surprise Valley (table 1). Analyses of waters issuing from Seyferth Hot Springs, Leonards Hot Springs, Surprise Valley Mineral Wells, and Lake City Hot Springs show that the water chemistry of these four groups of springs is similar and that they are apparently part of the same system (Mariner and others, 1978, p. 85). Chemical geothermometers, useful in predicting subsurface temperatures from ions whose concentrations are dependent upon temperature, suggest that the reservoir underlying the four groups of springs has an estimated mean temperature that might locally exceed 150°C (table 2). Such areas would have a potential to generate electricity. Reservoirs at Fort Bidwell and elsewhere in the valley are apparently somewhat cooler and are attractive for uses other than generation of electricity.

Surprise Valley is considered favorable for the discovery and development of low-temperature (approximately 30° to 90°C) geothermal resources other than those which are directly observable at the ground surface as hot springs (Sammel, 1979, p. 104). Low-temperature geothermal waters are believed to occur locally in extensive reservoirs within 1 km of the ground surface. Such aquifers are not associated with zones of high permeability (such as faults) that allow percolation to the surface and are usually discovered accidentally in Surprise Valley by residents who drill unsuccessfully for cold water.

Minor sinter has been deposited at both the Lake City Hot Springs and the Surprise Valley Mineral Wells, whereas cinnabar and metacinnabar have been reported at only the Surprise Valley Mineral Wells (Raab and Dickinson, 1969). Mild hydrothermal alteration also occurs throughout the Warner Mountains, adjacent to Surprise Valley to the west. In the field, this alteration is expressed as a pervasive green color that is caused by the presence of disseminated celadonite. Other secondary minerals, found mainly in joints and in cavities, include zeolites, carbonates, hyaline opal, and crystalline or cryptocrystalline varieties of SiO_2 (Duffield and Weldin, 1976, p. 11). This mineralization is probably Tertiary in age and is interpreted to predate uplift of the Warner Mountains.

The source of heat within the geothermal system is not fully understood, but it may be related to residual heat associated with late Tertiary silicic magma within the crust beneath the Surprise Valley-Warner Mountains area (Smith and others, 1978, table 1). Silicic magma chambers at shallow ($\leq$10 km) depths (Smith and Shaw, 1975, p. 59) appear to have a direct relationship with many large geothermal fields elsewhere. Duffield and Fournier (1974, p. 11, 12) have noted that, with one possible exception, all hot springs in Surprise Valley are no farther than 4.8 km from extrusive rhyolite and (or) rhyolitic plugs and that the most significant known geothermal resources of the area, found in the northern half of Surprise Valley, are associated with the most extensive and youngest rhyolite-obsidian outcrops in the Warner Mountains. The youngest of these rhyolites, with a K-Ar age of 7.1 m.y. (Smith and Shaw, 1975, p. 68), are interpreted to be coeval with the most recent emplacement of silicic magma beneath the area. Moreover, an equivalent K-Ar age on extrusive rhyolite? from 80 km north-northwest of Lake City, at the Cougar Peak, Oregon, geothermal area (fig. 2) suggests that the two systems might be heated by the same or related plutons (Smith and Shaw, 1975, p. 68 and 71). Until more information is gathered on the age, size, and location of the magma reservoir that is hypothesized to be the heat source for the system, estimates of the initial and remaining thermal energy in the magma reservoir cannot be made.

Alternatively, Surprise Valley thermal water may be heated by deep circulation along major faults in a region of higher-than-average heat flow, with or without a direct magmatic component of thermal energy. The heat source is unresolved at this time.

STRUCTURE

Surprise Valley is a graben located between the west-tilted Warner Mountains horst to the west and the Hays Canyon Range horst to the east, in Nevada [not shown on map]. An estimated 3800 m of vertical displacement between the Warner Mountains and Surprise Valley fault blocks has occurred along the Surprise Valley fault. Episodic normal slip along the fault began no more than 15 m.y. ago (Duffield and McKee, 1974) and has continued into the Holocene (Hedel, 1980, p. 42-86). The age and amount of the fault displacement between Surprise Valley and the Hays Canyon Range are not well known, but are probably similar to those of the Surprise Valley fault.

Brittle fracture of the Warner Mountains accompanied the late Tertiary and Quaternary uplift of the range as shown by faults of variable strike that offset the lithologic section. Similarly, subsidiary faults exist within the buried Surprise Valley block. Many of these structures are covered by great thicknesses of lacustrine and alluvial deposits and are detectable only by geophysical methods. Relatively youthful movements on others have propagated to the surface and are manifested as degraded fault scarps on the valley floor.

Structural control of hot springs, where thermal fluids are concentrated in permeable fault zones, is evident in Surprise Valley. Seyferth Hot Springs, Leonards Hot Springs, Surprise Valley Mineral Wells, and Squaw Baths Hot Springs are clearly localized along known or inferred faults. Lake City Hot Springs and Menlo Baths Hot Springs occur in highly fractured areas where faults of diverse trends converge. Fort Bidwell Hot Springs and Boyd Warm Springs may be associated with faults, but evidence for such faults is lacking.

Lake City Fault Zone

The Lake City fault zone has been recognized by geophysical techniques between Upper Lake and Middle Alkalai Lake as a northwest-trending cluster of fractures that is about 610 m wide with at least two principal strands (D.B. Hoover, unpub. data, 1975). In the western part of the valley, the fault zone is also expressed as a group of obscure, low scarps and photolineaments (Hedel, 1980, pl. 1). The northwest-trending, linear form of the southwestern shoreline of Upper Lake appears to be controlled by the position of the Lake City fault zone. To the southeast, the surface expression becomes progressively less distinct and eventually disappears beneath poorly consolidated lacustrine and eolian deposits, but geophysical data suggest the subsurface continuation of the fault zone to the east side of the valley (Ford and others, 1963, pl. 21). Anomalies of apparent resistivity, determined from audio-magnetotelluric (AMT) soundings, suggest that the Lake City fault zone splays to the south toward the Surprise Valley Mineral Wells (D.B. Hoover, unpub. data, 1975). If it does, the northwest-trending northeastern shoreline of Middle Alkalai Lake might also be controlled by faulting. The sense of motion along the fault zone is down to the northeast, with a possible lateral component of slip (Hedel, 1980, p. 40-41).

Several lines of evidence (D.B. Hoover, unpub. data, 1975) indicate that the Lake City fault zone is an area of high permeability that allows communication of thermal fluids between the east and west sides of the valley:

1) Water Quality: Figure 1 depicts an area of hazardous groundwater that is defined by high concentrations of boron, fluoride, sodium, and sulfate. The area of poor-quality water is coextensive with the Lake City fault zone and thus provides substantial evidence that the group of linear fractures function as a permeable zone across the valley.

2) Gravity Anomalies: Small gravity highs associated with the Lake City fault zone occur immediately below the southern extent of Upper Lake, away from hot spring areas. These anomalies are probably caused by local density increases caused by silica cement replacing calcium carbonate in basin-fill deposits within 90 m to 150 m of the ground surface. This suggests that hot mineralized fluids are or were present within the fault zone.

3) Magnetic Anomalies: Magnetic "noise" that accompanies gravity highs along the Lake City fault zone signifies the presence of magnetic minerals localized in the fault zone in otherwise nonmagnetic basin-fill deposits. Presumably, chemical reactions of hot saline fluids in the fault zone have generated small amounts of magnetic minerals within about 60 m of the surface.

4) Geothermal Ground Noise: Preliminary interpretation of anomalous levels of microseismic activity reveals a clear association of geothermal ground noise with the Lake City fault zone. Isoseismic lines encompass the Lake City Hot Springs and are distinctly elongated to the southeast along the Lake City fault zone, apparently outlining an area where thermal fluids migrate. (Similar anomalies also occur in Fort Bidwell; see Eng and Decker, 1974, and Eng, 1975.)

The Lake City fault zone clearly has an important affect on the location of geothermal resources in Surprise Valley. Significant hot spring activity in northern Surprise Valley appears to be localized where north-trending faults intersect the Lake City fault zone.

Volcano-Tectonic Lineaments

Two northwest-trending lineaments (fig. 2) have been inferred in the Surprise Valley-Warner Mountains area (Duffield and Fournier, 1974, p. 7-10). In the north, the Fandango fault zone is defined by a cluster of northwest-trending normal-slip faults (with a possible strike-slip component) in the vicinity of Fandango Valley in the Warner Mountains. Evidently, this area has acted as a hinge, because south of Fandango Valley the Warner Mountains block is tilted westward, whereas dips are eastward north of the valley. Rhyolite and obsidian are particularly abundant near the lineament. West of the Warner Mountains the lineament projects across Goose Lake and into southern Oregon.

To the south, a second lineament trends to the northwest from Hays Canyon Peak in Nevada, a Tertiary volcanic vent, across Surprise Valley, and through the Warner Mountains near Cedar Pass, the locus of two major Tertiary volcanoes. West of the Warner Mountains, it projects across the Devils Garden to include a zone of northwest-trending faults east of Carr Butte in northwestern Modoc County (Gay and Aune, 1958) and into southern Oregon where it has been mapped as the Mount McLoughlin fault zone. In Oregon, the lineament is thought to have offset the crest of the Cascade Range 15-20 km in a right-lateral sense during Quaternary time (Lawrence, 1976, p. 848). The only known outcrops of rhyolite and obsidian (Tertiary in age) in the Devils Garden are found along the lineament just west of Blue Mountain.

Both lineaments parallel the Lake City fault zone and the Likely fault (Gay and Aune, 1958), located west-southwest of the Warner Mountains. Collectively, these features define a northwest-trending structural grain through northeastern California. Some of these structures have been the locus of reported late Cenozoic volcanism. In Surprise Valley and elsewhere in northeastern California, attractive areas for geothermal exploration might occur along these faults and lineaments.

GEOTHERMAL PROSPECTING AND DEVELOPMENT

Commercial exploration of the Surprise Valley geothermal area began in the late 1950's. To date, actual development by private industry includes ten test wells which range in depth from 28 m to over 2100 m. Bottom-hole temperatures in test wells (table 3), where known, are in reasonably close agreement with subsurface temperatures predicted from water chemistry of hot springs (table 1). With present technology, maximum reservoir temperatures are marginal for generating electricity. However, hot spring resources are adequate and could be enhanced by flow from wells to support nonelectric commercial developments. Uses such as heating greenhouses, drying lumber in wood kilns, warming feed lots and agricultural fields for winter crops, and space heating of commercial, residential, and public buildings are economically practical and readily achievable applications of geothermal energy in Surprise Valley (California Division of Oil and Gas, unpub. report, 1977). At present, some buildings at Surprise Valley Mineral Wells and at Menlo Baths are heated by hot water, but nearly all geothermal resources are unused.

GEOTHERMAL DEVELOPMENT AND EARTHQUAKE HAZARDS

As with many of the deep, fault-bounded structural valleys in the Great Basin, Surprise Valley is tectonically active. The Surprise Valley fault has apparently generated magnitude 7+ earthquakes during the Holocene Epoch, and events of this size are likely to recur (Hedel, 1980, p. 91-103). Late Quaternary surface rupture has occurred along the range-front fault as well as along many strands on the valley floor, including the western part (and possibly the entire length) of the Lake City fault zone, although there is no record of significant historic seismicity in Surprise Valley. The best producing geothermal wells and any related industrial buildings are likely to be located along or near these faults. If so, seismic risks, both natural and induced, must be considered in the development of the geothermal resources. Moreover, faulting during an earthquake can greatly affect the longevity of geothermal reservoirs, as discharge from hot springs and wells may be greatly enhanced or diminished by seismically induced changes in permeability.

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Table 1.-- Location and temperatures of hot springs in Surprise Valley

[Data from Duffield and Fournier, 1974, p. 8a and 12a, and Reed, 1975, p. 24.]

Springs	Location	Maximum measured surface temperature (°C)	Maximum predicted subsurface temperature (°C) Quartz	Na-K-Ca	Visually estimated rate of flow (liters/sec)	Comments
Fort Bidwell Hot Springs (2 springs).[1]						
A	Sec. 17, T. 46 N., R. 16 E.	46	133	180	~200	Flow is through a corroded well-casing pipe.
B	Sec. 8, T. 46 N., R. 16 E.	43	---	---	≤150	Water used domestically.
Boyd Warm Spring . .	Sec. 31, T. 45 N., R. 17 E.	20	---	---	150-300	Shows as hot spring on topographic map but is actually a warm spring.
Lake City Hot . . . . Springs	Secs. 13 and 24, T. 44 N., R. 16 E.	89	174	160	≤150?	Area of mud-volcano eruption in 1951 (see White, 1955).
Seyferth Hot Springs	Near common corner of secs 1, 2, 11, 12, T. 43 N., R. 16 E.	87	144	130	≤150	
Leonards Hot Springs (2 springs).						
A	Near common corner of secs 7, 12, 13, 18, T. 43 N., R. 16 E., and R. 17 E.	66	146	121	150-300	Located about 1 km NNE of old Leonard Spa bathhouse.
B	Sec. 13, T. 43 N., R. 16 E.	41	108	107	150-300	Located at bathhouse.
Surprise Valley Mineral Wells (4 groups of springs).[2]						
A	Near center of sec 6, T. 42 N., R. 17 E.	87[3]	135	116	150-300	Flow is from 2 wells at lodge; used for winter heating.
B	Sec. 6, T. 42 N., R. 17 E.	93[3]	---	---	300-600	Flow from a cluster of 4 springs.
C	SW 1/4 sec. 6, T. 42 N., R. 17 E.	98	140	118	300-600	Flow is from 2 springs about 1/2 km SW of lodge.
D	SE 1/4 sec. 1, T. 42 N., R. 16 E.	93[3]	135	118	~400	At abandoned shack about 1 km SW of lodge.
Menlo Baths Hot Springs (2 groups of springs).						
A	NE 1/4 sec. 7, T. 39 N., R. 17 E.	59	105	61	150-300	Nearly all warm well water 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	SE 1/4 sec. 6, T. 39 N., R. 17 E.	53	---	---	≤150	Flow comes from several small seeps in hillside.
Squaw Baths Hot Springs (3 groups of springs).						
A	NE 1/4 sec. 29, T. 39 N., R. 17 E.	43	---	---	≤150	Three springs are within 100 m of one another alined approximately south-north (C--A) in the road ditch of Surprise Valley Road
B		42	---	---	150-300	
C		35	---	---	≤150	

1 Geothermometer temperatures may be unreliable; low surface temperatures may be nearer minimum subsurface temperature estimates, or water may be mixed.
2 Water is boiling at all springs.
3 Temperatures where thermometers could not be submerged directly in the throat of a spring -- probably a few degrees too low. Many springs show some evidence of carbonate deposition and a few showed minor SiO_2 deposition.

Table 2.-- Estimates of temperatures, volumes and thermal energies for geothermal reservoirs of the Fort Bidwell and Lake City areas.
[Data from Brook and others, 1979, p. 46 and 62.]

Location of reservoir		Estimates of reservoir temperature* (°C)	Mean reservoir temperature (°C)	Mean reservoir volume (Km^3)	Mean reservoir thermal energy (10^{18} J)	Wellhead thermal energy (10^{18} J)	Wellhead available work (10^{18} J)	Electrical energy (megawatts electrical for 30 yr)	Beneficial heat** (10^{18} J)
Fort Bidwell	Most likely:	126[2]							
	Max:	179[3]	135 ± 17	3.3 ± 0.9	1.08 ± 0.34	0.27	0	0	0.060
	Min:	99[1]							
Lake City-Surprise Valley Mineral Wells area	Most likely:	143[2]							
	Max:	185[4]	152 ± 12	210 ± 90	79 ± 32	19.8	3.5	1490	---
	Min:	129[3]							

* Chemical geothermometers used for reservoir temperature estimates. See Brook and others (1979, p. 21) for methodology, assumptions, reliability, etc.
1 Chalcedony.
2 Quartz conductive.
3 Na-K-Ca.
4 Subjective estimate.
Present technology demands geothermal resources with tempertures ≥ 180°C for generation of electricity.
** Beneficial heat is the amount of resource that could be directly applied to nonelectric uses (e.g., space heating).

Table 3.-- Geothermal test wells drilled in Surprise Valley
[Compiled from Duffield and Fournier, 1974, Reed, 1975, and the Petroleum Information Corporation, 1979.]

No.	Well name	Total Depth (feet/meters)	Bottom hole temperature (°C)	Time between temperature measurement and last circulation of drilling mud	Type of log(s) run and depths	Location	Company	Drilling dates	Status
1	Parman 1	2150/ 655	140	1 year	2150 ft, electric and temperature.	Sec. 24, T. 44 N., R. 15 E.	Magma Energy	07/02/1959-07/20/1959	Idle
2	Parman 2	1968/ 600	> 125	Flow-line temperature	1968 ft, electric and temperature.	Sec. 24, T. 44 N., R. 15 E.	do.	07/21/1959-07/26/1959	do.
3	Parman 3	92/ 28	---	---	92 ft, temperature.	Sec. 24, T. 44 N., R. 15 E.	do.	07/26/1959-08/09/1959	Abandoned (blowout)
4	Cedarville 1	734/ 223	54	15 hours	Unknown	Sec. 6, T. 42 N., R. 17 E.	do.	07/06/1962-07/25/1962	Abandoned
5	Phipps 1	1267/ 386	137	64 hours	1267 ft, temperature.	Sec. 24, T. 44 N., R. 16 E.	do.	08/13/1962-09/17/1962	Idle
6	Phipps 2	4512/1367	~160° at 3788 ft (1155 m).	Unknown	4512 ft, electric and temperature.	Sec. 24, T. 44 N., R. 16 E.	do.	11/13/1972-12/26/1972	Idle?
7	Surprise Valley 1-ST	6841/2086	Unknown	do.	Unknown	Sec. 30, T. 44 N., R. 16 E.	Gulf Oil	08/21/1973-09/12/1973	Idle
8	Surprise Valley 2-ST	6505/1983	do.	do.	5500 ft electric.	Sec. 13, T. 43 N., R. 16 E.	do.	09/17/1973-10/22/1973	Abandoned
9	Phipps 2 (deepened original hole).	4946/1508	do.	do.	4946 ft, electric and temperature.	Same as No. 6	Magma Energy	10/03/1974-12/10/1974	Idle?
10	Goodwin 1-11	7005/2135	do.	do.	Unknown	Sec. 11, T. 42 N., R. 16 E.	American Thermal Resources	11/22/1974-12/20/1974	Abandoned
11	Hapgood 1	Unknown	do.	do.	do.	Sec. 13-14, T. 44 N., R. 15 E.	Magma Energy	Unknown	Idle

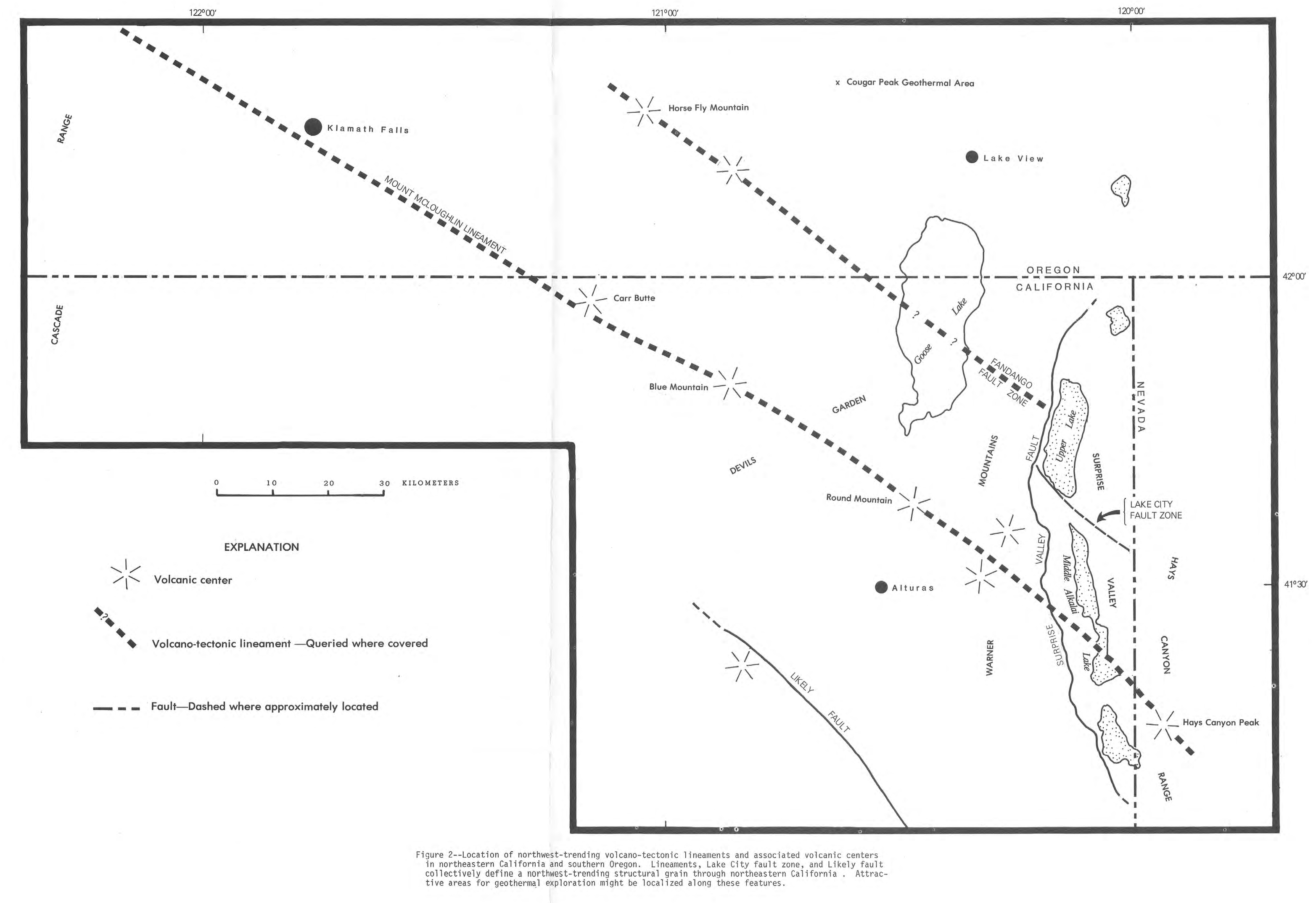

Figure 2--Location of northwest-trending volcano-tectonic lineaments and associated volcanic centers in northeastern California and southern Oregon. Lineaments, Lake City fault zone, and Likely fault collectively define a northwest-trending structural grain through northeastern California . Attractive areas for geothermal exploration might be localized along these features.

Interior--Geological Survey, Reston, Va.--1981

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MAP SHOWING GEOTHERMAL RESOURCES OF THE LAKE CITY—SURPRISE VALLEY KNOWN GEOTHERMAL RESOURCE AREA, MODOC COUNTY, CALIFORNIA

Compiled by
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1981