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RESOURCE ASSESSMENT OF LOW- AND MODERATE-TEMPERATURE GEOTHERMAL WATERS IN CALIFORNIA

Report of the First Year, 1978-79 of the
U.S. Department of Energy-California State-Coupled Program
for
Reservoir Assessment and Confirmation

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I. INTRODUCTION

Information on geothermal resources in California, as in many other western states, has been scattered and incomplete, particularly for the low- and moderate-temperature resources, which are defined respectively as $< 90°C$ and 90-150°C. This is because these resources have not been considered economically exploitable. The abundance of low cost, portable petroleum-based energy has previously neutralized incentives to develop geothermal energy in most parts of the state.

To stimulate the development of geothermal energy, the Department of Energy (DOE) established the state-coupled cooperative program in which an appropriate group in each participating state is funded to compile existing information and to perform reservoir assessment and confirmation studies. Basic data are fed into the U.S. Geological Survey's GEOTHERM data bank. Interpretive studies are submitted to the DOE for publication. A state map showing areas of low- and moderate-temperature resources in California will be published in 1980 from data produced by this project.

APPROACH

For organizational purposes, DOE has defined two operationally distinct technical phases in the program. Phase I involves the compilation, verification, and dissemination of existing data, as well as use of this data to produce state geothermal maps and related publications and to assess regional and local geothermal areas. Phase II involves site specific studies in which new data are generated by geophysical surveys and drilling operations. The data are used to quantitatively assess the resource potential of a given geothermal reservoir.

In this, the first year of the program, emphasis was placed on Phase I studies because of the obvious need for an organized set of background geothermal data for use by individuals and groups wishing to exploit low- and moderate-temperature geothermal resources. Less effort was devoted to a Phase II study at Bridgeport, a site with potential geothermal application already of interest to the California Department of Transportation for a highway maintenance facility.

To accomplish the work, two geologists and three student assistants were assigned to data collection tasks, a senior geologist was assigned as program manager, and two geophysicists and a part-time assistant were assigned to Phase II studies. A geochemist was assigned to set up laboratory procedures for analysis and to advise the staff on chemical or potential environmental problems.

II. DISTRIBUTION OF GEOTHERMAL RESOURCES IN CALIFORNIA

The Geothermal Map of California (Plate 1) shows that the major zones of geothermal activity lie along the interior and coastal margins of the state. In that marginal area lie the geothermal resource areas that have been of interest for high-temperature exploitation: The Geysers-Clear Lake area in the Coast Ranges north of San Francisco, Surprise Valley in the Modoc Plateau area, Long Valley and Coso Hot Springs in the Basin and Range area, and the Imperial Valley at the southern boundary of the state. A distinct belt that exhibits minimal or no geothermal activity extends from the northwest corner of the state, through the Klamath Mountains, the Great Valley and the Sierra Nevada Mountains. Evidence of geothermal activity increases as this belt continues southeastward through the Lake Isabella region and eastward across the Mojave Desert to Needles and the eastern extremity of the state.

This distribution indicates some obvious though not universal associations of crustal structure to geothermal activity and prompts the following discussion of geothermal areas grouped according to region. The regions discussed here are essentially the geomorphic provinces defined by Reed (1933) and Jenkins (1938) with some variations to accommodate differences in geothermal activity and current thought on tectonism and volcanism. The distribution of near surface geothermal phenomena reveals an apparent close association with recent volcanism and recent crustal deformation, particularly tensional tectonics. On Plate 1, six provinces of geothermal significance are outlined:

1) Klamath-Sierra province and the Isabella subprovince
2) Cascade-Modoc province
3) Coastal Ranges and The Geysers subprovince
4) Basin and Range province
5) Mojave Desert province
6) Salton Trough province

This discussion of geothermal activity according to regions is tentative because it implies the existence of a clearly defined scheme of separating geothermal provinces. As knowledge of geothermal activity and related geology accumulates, the validity of that concept or scheme can be tested.

In the following description of the geothermal provinces, the following associations are noted: volcanic activity, heat flow, nature of faults and seismicity, crustal structure in general, and physiography. Discussions of heat flow are based upon U.S.G.S. data published by Sass and others (1976). Discussions of seismicity are based upon the Division of Mines and Geology Earthquake Epicenter Map by Real, Toppozada and Parke (1978). Volcanic rock distribution shown in Figure 1 was compiled from data on the 1977 Geologic Map of California. The distribution of mineralized or hydrothermally altered zones, compiled from numerous sources is shown in Figure 2.

Cascade-Modoc Province

The Cascade-Modoc Province, in the northeast corner of the state, contains both the southern end of the Cascade Range, which is characterized by abundant youthful andesitic volcanoes, and the Modoc Plateau, which is marked by massive volcanic flows and domes. These areas are, to some

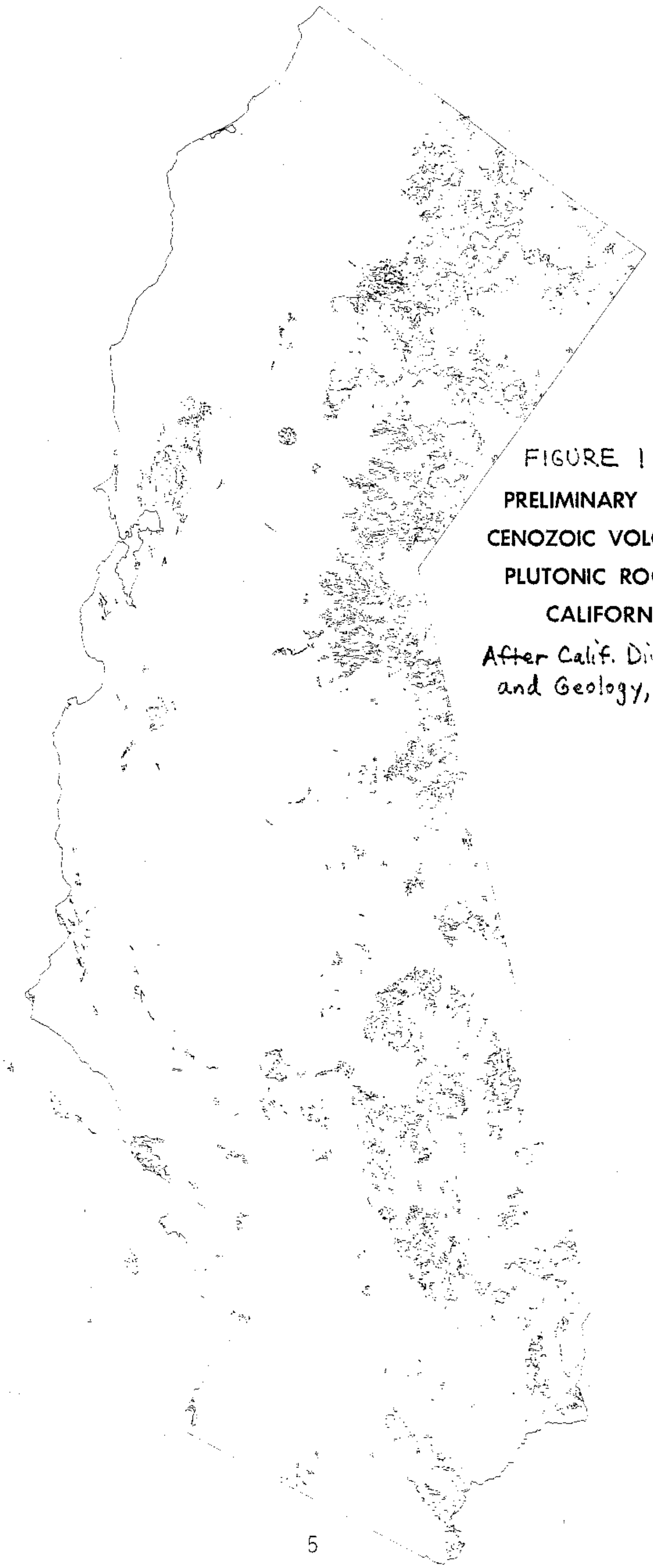

FIGURE 1 – PRELIMINARY MAP OF CENOZOIC VOLCANIC AND PLUTONIC ROCKS IN CALIFORNIA

After Calif. Div. Mines and Geology, 1977.

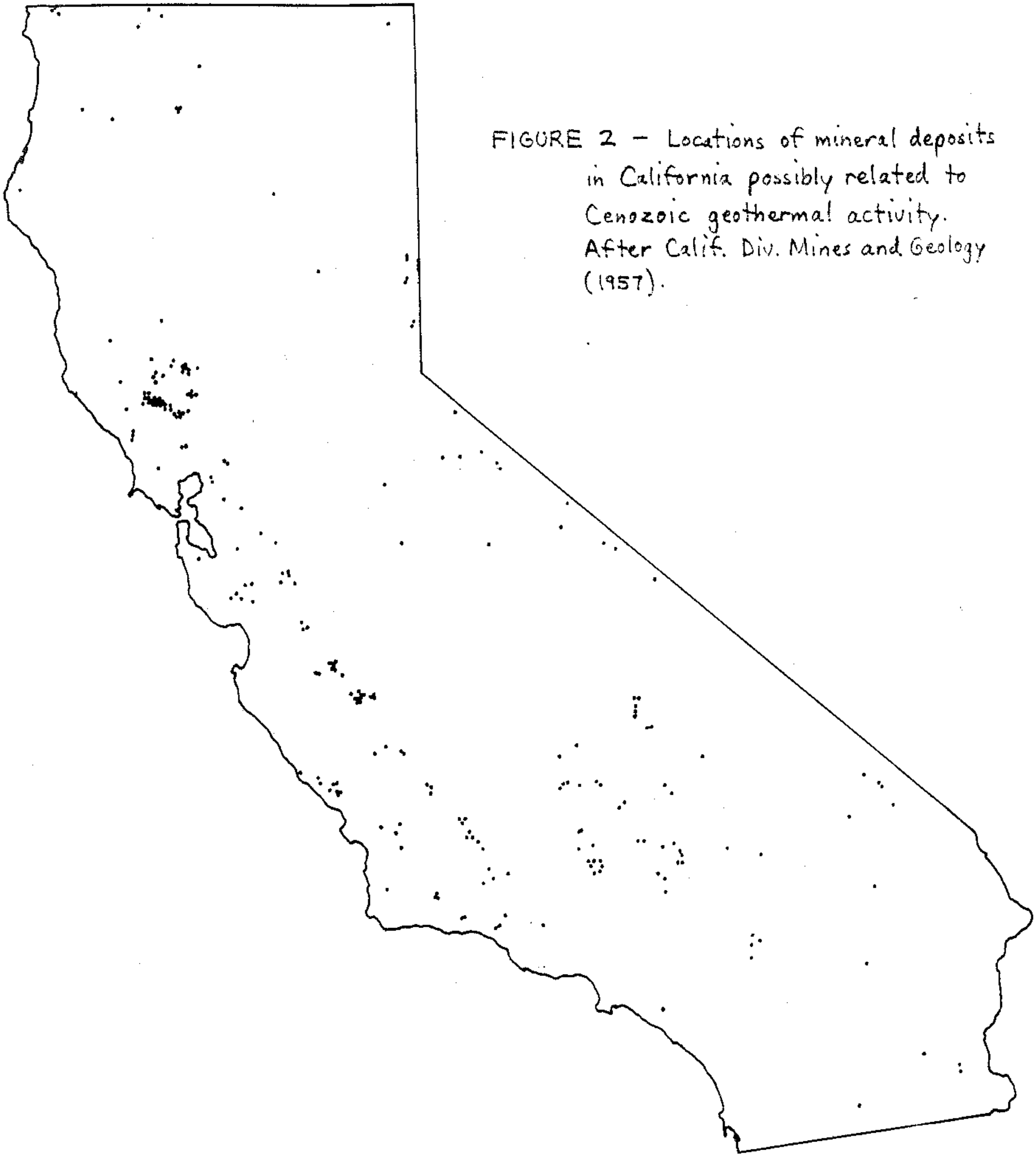

FIGURE 2 – Locations of mineral deposits in California possibly related to Cenozoic geothermal activity. After Calif. Div. Mines and Geology (1957).

extent, unified by the development of basin-range fault structure, which pervades the entire region. The faults here trend dominantly NNW and many show evidence of Quaternary displacement. The Modoc region appears to have had a history of consistently recurring volcanism from mid-Tertiary through Holocene time. Quaternary faulting has occurred broadly across the province, and geothermal fields in the area are clearly related to recent volcanism, and appear to be scattered at random across the province.

Regional heat flow according to Sass and others (1976) is moderate to high based upon limited data. Seismicity during the period 1900 to 1974 was moderate in a belt extending from Lake Tahoe to Lassen Peak and northward, but abundant evidence of Holocene and Pleistocene faulting suggests that this short period of observation is not representative of recent seismicity in the province.

This region shows promise for geothermal development for direct applications and possibly electric generation. It includes geothermal fields at Surprise Valley, Kelly Hot Springs, Likely, Susanville, Wendel-Amedee and Lassen, all of which are the subject of commercial exploitation for electric or direct heat application. Other geothermal areas currently of interest are Glass Mountain, Sierra Valley, Mount Shasta and the eastern side of Goose Lake.

The Modoc-Cascade region contains five known geothermal resource areas (KGRA's): Glass Mountain, Lassen, Lake City (in Surprise Valley), Wendel-Amedee and Beckwourth Peak.

Basin-Range Province East of the Sierra Nevada

This province is pervasively faulted but the nature of the volcanism and tectonism differs from that of the Cascade-Modoc province. East of the Sierra Nevada, the Basin-Range province experienced intensive and widespread volcanism mainly in the Tertiary; but later volcanism has been limited to a zone of active faulting and deformation along the eastern front on the Sierra Nevada Range. In that zone are the recently active volcanic centers and geothermal fields of the Mono Basin-Long Valley area and the Coso volcanic center. At the northern extremity of this zone are Fales Hot Springs, Grovers Hot Springs, and The Hot Springs and Travertine Hot Springs, which are near Bridgeport. The greatest potential resource in this province is believed to be the Long Valley caldera, where massive ignimbrite eruptions in the late Pleistocene were followed sequentially by large-scale volcanic collapse and resurgent eruption of rhyolitic domes and shallow intrusives. Within the caldera, the Casa Diablo geothermal field has potential for electric generation. Several areas of low- to moderate-temperature water are known. The resort town of Mammoth Lakes is planning a municipal district heating network. A second major geothermal resource is Coso Hot Springs, within the U.S. Naval Weapons Center. Here a small geothermal electric generation plant is planned.

Outside of the Sierra frontal fault and volcanic zone, a potential geothermal resource is found in Saline Valley in a zone of Quaternary faulting on an extension of the Panamint Valley fault zone. Other isolated occurrences of which little is known are the Tecopa Hot Spring area, near Shoshone, Trona, and possibly the Ridgecrest-China Lake area.

In the southernmost part of the province some relatively unknown low-temperature geothermal fields are located in the Twentynine Palms, Desert Center and Nicolls Warm Springs areas. These are relatively unstudied areas. One can speculate at this time that they are genetically related to the crustal stretching phenomena operating in the Salton Trough.

Designated KGRA's in the Basin-Range Province are Long Valley, Coso Hot Springs, Bodie, and Saline Valley.

In the Basin-Range Province, emphasis has been and probably will continue to be placed on exploration for high-temperature waters for electric generation. Because of the sparsity of population, direct heat applications are currently of interest mainly in the few towns near thermal areas, notably, Mammoth, Bridgeport, Trona, Tecopa, and Bishop.

Klamath-Sierra Province

This region shows little evidence of geothermal activity and does not appear promising as a source of moderate- or low-temperature waters. The Klamath Mountains make up the northern portion of the province. This is a relatively stable mass of Paleozoic and Mesozoic metasedimentary and metavolcanic rocks, that are intruded by igneous bodies as young as Late Mesozoic age.

The Sierra Nevada Mountains and the Great Valley lie to the south. This area is underlain by the Sierra Nevada Batholith, a large, uplifted granitic block tilted westward beneath younger sediments of the Great Valley. The plutonic rocks range from Triassic to Cretaceous in age.

The entire province coincides with a conspicuous low heat flow anomaly mapped by Sass and others (1976) in which values as low as 19 mw/m^2 (milliwatts/square meter) are recorded. Seismicity is also low in this region except near Cape Mendocino, at the western extremity of the province.

Isabella Subprovince

The Isabella subprovince makes up the southern end of the Sierra Nevada immediately west of the Basin-Range province. This area contains twelve known hot springs. Regional heat flow is unknown, but the presence of hot springs and recently discovered faults of basin-range extensional nature suggest that this area may not be typical of the Sierra Nevada block. This region is one of the more seismically active parts of the state.

Relatively little is known about any of the thermal springs in this subprovince. Seven hot springs are aligned arcuately along the course of the Kern River near Lake Isabella. It is assumed that the springs are the result of circulation on deep seated faults, hence, the discovery of a large or high-energy geothermal reservoir in this province is not anticipated. Nonetheless, several small communities in the vicinity of Lake Isabella could make effective use of low- and moderate-temperature waters found there.

Coastal Range Province

The Coastal Range province, is an approximately 80-km wide strip extending along the California coast from the Mexican border nearly to Cape Mendocino. It is a zone of fold mountains with stresses that give rise to the right-lateral San Andreas Fault system.

Variations of the stress pattern exist in the Transverse Ranges, north of Los Angeles, where active compressional tectonics are evident, and also at opposite ends of the province in areas 65 km or more from the San Andreas Fault, where the transcurrent stresses are less evident.

The northern part of the Coastal Range province contains a zone of Pliocene to Holocene volcanic activity. Associated with this are The Geysers, Calistoga, and smaller but significant geothermal fields of the Clear Lake area. Beginning in Pliocene time and continuing into Holocene time, the volcanic activity migrated northward from Napa Valley into the Clear Lake area. The heat source for The Geysers geothermal field is believed to be a subsurface magmatic body (Chapman, 1975) associated with the recent Clear Lake volcanism. Several moderate- and low-temperature reservoirs are known on the periphery of The Geysers field, and more high-temperature fields are being actively sought. Peripheral geothermal resources are known at Calistoga, Collayomi and Cobb Valleys, Sulfur Bank, and Wilbur Springs. The U.S. Geological Survey has designated KGRA's at Lovelady Ridge, Knoxville, Witter Springs, and Little Horse Mountain in The Geysers peripheral area.

South of this area, there is little evidence of volcanic activity since Miocene time. Conspicuous geothermal activity generally consists only of isolated hot springs on deep-seated faults or of diffuse bodies of warm subsurface water evidently formed by mixing of deep-seated, rising geothermal water with ground water in shallow aquifers. Examples of the latter are found at Paso Robles in San Luis Obispo County and at Imperial Beach in southern San Diego County. In the Transverse Ranges, several hot springs are aligned along the Elsinore and San

Jacinto faults in the southern end of the province, and on the Rinconada and related Coast Range faults in Monterey County in the central part of the province. None of these hot spring areas have been studied in detail. Their heat source is evidently of deep seated origin.

Heat flow is highest in the northern geothermally active portion, as far south as the Hollister area, where values range from 70 to 96 mw/m^2 (Sass and others, 1976). Southward, in the Transverse Ranges, heat flow values are in the low 70's, and fall close to 50 mw/m^2 and below in the San Diego area.

Seismic activity is relatively high in the Hollister and Los Angeles-Huntington Beach areas, where higher than average heat flows exist, and low in The Geysers and San Diego areas where contrasting geothermal conditions are found. Thus, whereas heat flow correlates marginally with geothermal activity, seismicity appears to be independent of geothermal activity.

Mojave Desert Province

The Mojave Desert province is a region of relatively low known geothermal activity south and west of the Basin-Range province. The topography is more mature than in the Basin-Range province, yet the area is more active seismically. Like the Coastal Range province to the west, the Mojave is transected by a series of active and potentially active NW-trending faults related to San Andreas system. Among these are the Ludlow, Calico, Camp Rock, Lenwood and Helendale faults. A few isolated, fault-related hot springs are known in the region. Potentially, the most important known resource in the province is at

Randsburg, which is a KGRA.

Regional heat flow in the province is moderate; Sass and others (1976) report values close to 68 mw/m^2. No pronounced heat-flow anomalies are known. Seismic activity in this region is relatively high and is associated with Quaternary and historic faulting especially along the San Andreas fault, the Manix fault, and other strike-slip faults mentioned above.

Salton Trough Province

The Salton Trough province contains both the high enthalpy geothermal fields of the Imperial Valley and several low and moderate-temperature fields. It is a wedge-shaped area incorporating the area lying between the San Jacinto fault and the San Andreas fault.

The Salton Trough, in the southeastern half of this province, is one of the most geologically unstable parts of California. It is considered a spreading center in which the crust is extremely thin, and heat flow is greater than 100 mw/m^2. Surface volcanism has not been widespread, but Holocene and Pleistocene extrusives are exposed at the southern end of the Salton Sea and near Cerro Prieto (Mexico). This region is also among the most seismically active in California. Earthquakes here are commonly associated with surface fault movements; historical displacements have been observed on the Imperial, Superstition Hills, Coyote Creek, San Andreas, and Casa Loma faults.

Apart from the high-temperature resources of the Imperial Valley and its immediate periphery, other geothermal areas occur at San Bernardino, near the convergence of the San Jacinto and San Andreas faults, and at Desert Hot Springs. These thermal areas appear to be caused by deeply circulating waters rising along the San Andreas and San Jacinto faults and the frontal faults of the Little San Bernardino mountains, respectively.

III. GEOLOGIC ASSOCIATIONS WITH GEOTHERMAL ACTIVITY

Early workers have noted the association of geothermal resources with active volcanoes, and later, with worldwide zones of mountain building or crustal instability, such as the "Pacific Rim of Fire". On a smaller scale, these associations are found in California. Of the ten most promising geothermal areas, all show evidence of nearby recent volcanism. These areas are also subject to recent crustal deformation, particularly tensional faulting. In contrast, the region containing the least geothermal activity, the Klamath Mountains-Sierra Nevada province, is marked by relatively low tectonic activity and practically no volcanism since Mesozoic time.

In analyzing the goethermal potential of different regions of California, notes were made of the incidences of correlation of the following features with geothermal activity: Tertiary volcanic rocks, Quaternary volcanic rocks, areas of unusual crustal activity or stability, seismicity, Quaternary faults, older faults, and heatflow. These conditions are shown in Table 1 in which geothermal correlation features are listed for each of the geothermal provinces shown on Plate 1.

Tertiary Volcanic Rocks

The association of Tertiary volcanic rocks with known geothermal activity is fairly strong only in the Cascade-Modoc province, the southern portion of The Geysers geothermal region, and the Klamath-Sierra province.

In the Modoc region both Tertiary and Quaternary volcanics are almost ubiquitous and geothermal activity is also abundant. Because of this overlap it is difficult in most cases to distinguish the association of geothermal activity and Tertiary volcanism from that of Quaternary volcanism. In the greater Geysers area in the Coastal Range province geothermal activity occurs in the Tertiary Sonoma Volcanics, which occupy the southern part of the Mayacmas Range from St. Helena southward to the San Francisco Bay Area. This association is not complete, for major known geothermal fields lying north of St. Helena are associated with Quaternary volcanics of the Clear Lake series.

In the Klamath Mountains and Great Valley areas (Klamath-Sierra province) the association is complete in that there is a general absence of both Tertiary volcanics and geothermal activity. The association breaks down, however, in the northeastern Sierra Nevada, where a widespread mass of Tertiary volcanics (the Mehrten Formation) occurs in a low heat flow terrain with negligible geothermal activity. Similar negative correlations occur in the Mojave province.

Quaternary Volcanic Rocks

Excellent positive correlations of geothermal activity with Quaternary volcanism are observed in the Cascade-Modoc province, the Coastal Range province and the Basin and Range province. Correlation is even more profound in the Klamath-Sierra province, where both geothermal activity and Quaternary volcanism are virtually absent.

A negative association was noted in the portion of the Basin Range province lying just east of the Mojave Desert province, where three clusters of Holocene cinder cones lie in areas of no known geothermal activity. The subsurface geology of this region is not sufficiently known to state with certainty that geothermal activity is lacking.

Crustal Activity

The correlation of geothermal activity with crustal activity in general, i.e. folding, faulting, regional warping, and seismic activity, is stronger in California than the correlation of geothermal activity with Quaternary volcanism. This positive association exists clearly in all geothermal provinces, except possibly the Mojave, which has low geothermal activity and relatively high tectonic activity in the form of recent strike-slip tectonics and high seismicity.

Mineral Deposits

Hydrothermal mineral deposits and areas of hydrothermal alteration in California are shown in Figure 2. Most of the areas shown are fossil hydrothermal effects, some as old as Mesozoic. Comparison with Plate 1 shows that there is very little correlation between fossil hydrothermal activity with current geothermal activity. The Coast Ranges are marked by a linear distribution of mercury deposits showing evidence of very recent if not current hydrothermal activity. At Sulphur Bank (Clear Lake), there is a clear association of present day mercury mineralization and current geothermal activity. The mercury-geothermal association in the Coast Ranges was recognized as early as 1888 by Becker and the suggestion that mercury deposits might be useful as exploration aids for geothermal resources was noted by Donald White (1955).

Age Relations

Application of these geothermal-associated features as exploration aids requires consideration of age relations, for the correlations are definitely higher for youthful than for older features. This is especially true for the correlation between hydrothermal mineral deposits and geothermal activity.

Most hydrothermal activity occurs at depth and the alteration zones are exposed at the surface only after a long period of uplift and erosion. During this time, local heat anomalies will have in general, cooled to regional levels. Hence, before hydrothermally altered rocks can be used as indications of subsurface geothermal activity, a detailed understanding of the local geology is required; specifically, the age and depth of the alteration process, as evidenced by the nature of the mineralization, the age of the altered country rock, and the tectonic and geomorphic history of the area.

This same principle applies also to the recency of volcanism and faulting. Just as current geothermal activity is more related to present day tectonic belts than to Palezoic tectonic belts, major geothermal areas in California lie in the currently more active tectonic zones, notably those in which volcanism is a tectonic ingredient. Detailed analysis of the effect of recency of faulting on the correlation, however, is complicated by the state-of-art knowledge of active faulting in California. Resource data for fault correlation criteria was the Fault Map of California (Jennings, 1975). As geologic work progresses, may of the older mapped faults are proving to be Quaternary or even active. A possible effect of this on Table 1 is the relatively similar correlations of geothermal activity and older faults and Quaternary faults in the Cascade-Modoc province and in the Coastal Range province. As fault studies progress further, it may prove that many of the older faults are indeed Quaternary, and shift the apparent correlation of geothermal activity more strongly toward the more youthful faults.

In the Klamath-Sierra and Isabella provinces, this shift is not so likely to occur. Here the association of geothermal activity with older faults is shown strongly in Table 1, and gives an insight of two distinct types of geothermal phenomena: that associated with volcanism and faulting in the more crustally mobile parts of the state, and that manifested by limited hot spring occurrences on faults in older, more stable and non-volcanic parts of the state. The latter type includes the major geothermal areas such as The Geysers, Coso Hot Springs and Long Valley where the effects of faulting are incidental to volcanism. In the non-volcanic occurrences, the nature of the heat source is not clearly understood, but surface vents occur on both Quaternary and older faults as if the fault serves only as a conduit as a means of easy passage of thermal water to the surface.

TABLE 1 CORRELATION OF GEOTHERMAL ACTIVITY TO VARIOUS
GEOLOGIC AND GEOPHYSICAL FEATURES

Geothermal province and approximate number of geothermal sites		Tertiary Volcanics	Quaternary Volcanics	Crustal Activity	Faults Quat.	Faults Older	Seismicity	Heat Flow
Cascade-Modoc	22	80	80	90	15	20	20	75
Coastal Ranges	25	5	3	72	60	95	80	50
The Geysers	35	77	80	90	+10	32	30	75
Klamath-Sierra	3	50	95	80	nil	95	75	100
Isabella	7	50	40	60	15	85	50	ID
Basin & Range	38	60	75	90	20	25	60	75
Mojave	4	30	15	50	50	ID	25	25
Salton Trough	35	50	50	100	90	10	95	95

Figures represent approximate percent of correlating features with geothermal activity for each of the listed provinces at the left. Complete 1:1 association of a geologic feature with geothermal activity would rate 100. A random correlation of a feature with geothermal activity rates 50. Figures below 50 indicate negative associations. Cases of double negative occurrences (e.g. Klamath-Sierra province has virtually no geothermal activity and virtually no Quaternary volcanics) also rate a high positive percentage correlations according to this scheme. Thus: A:B high incidence of both A and B, 100%

A:B random correlation, 50%

A:B high incidence of A, none of B, 0%

A:B absence of A and B, 100%

IV. INVENTORY OF PROMISING GEOTHERMAL RESOURCE AREAS

Based upon the collection and brief evaluation of statewide geothermal data, prioritized lists of promising geothermal areas or sites were prepared. These are presented in Tables 2, 3, and 4, which list geothermal areas in the high-, moderate-, and low-temperature ranges, respectively.

Rating Criteria

In judging the potential value of each site, two principal parameters were considered: (1) the magnitude of the resource and (2) the value of the resource in terms of its usefulness to society. This value may be termed its application potential.

The "magnitude of the resource" refers essentially to the heat energy content of the resource, in terms of Joules, BTU's or megawatt equivalents of electric energy. Geothermal resource areas in Tables 2, 3, and 4 are primarily listed by estimated energy magnitude, based upon temperature and presumed volume of the geothermal reservoir. In the case of individual hot springs, resource rating criteria were limited to discharge rate and temperature, for these were generally the only data available.

Table 2 lists high-temperature geothermal resource areas other than the well-known Imperial Valley and The Geysers production fields. Although high-temperature resources are beyond the scope of this study, Table 2 has been compiled and included here because of the potential usefulness of the peripheral areas for direct heat applications. Tables 3 and 4 include moderate- and low-temperature resource areas or sites listed generally in order of decreasing estimated energy magnitude.

Again, it is emphasized that the listing order is highly subjective because quantitative resource assessment data is in most cases insufficient. Chemical thermometry data have been important in estimating energy magnitudes in Table 3. The mean reservoir thermal energy and beneficial heat energy calculations presented in USGS Circular 790 have been respected in our rating process, with the realization that those calculations, too, are derived from preliminary or insufficient quantitative resource assessment data.

The low-temperature geothermal sites listed in Table 4 present the greatest problems in assessment, for these have received the least study; consequently, estimates of maximum reservoir temperature based upon chemical thermometry are generally lacking.

Application Potential

A complete assessment of the potential value of a low- or moderate-temperature geothermal resource must consider, in addition to the physical magnitude of the resource, its potential for application. This includes such factors as population density near the resource, needs in terms of space heating, agricultural, or industrial uses, and other societal or technical factors relating to the feasibility of application. The latter would be affected by water quality, which could present technical drawbacks for use of heat exchanger or other hardware subject to corrosion or scaling, and would also present problems of disposal for the waste geothermal water. These subjective qualities relating to application potential are taken into consideration in Table 5, prepared by Syd Willard of the California Energy Commission.

TABLE 2

RESERVOIRS > 150°C (HIGH TEMPERATURE)

NAME	°C MAX MEASURED TEMPERATURE	ESTIMATED ELECTRICAL ENERGY (MWe for 30 yr)
Long Valley	181	2,100
Cedarville (Surprise Valley)	160	1,490
Clear Lake area	270?	900
Coso Hot Springs	189	650
Morgan Springs	95	116
Sulphur Bank (exclusive of Clear Lake area)	186	75
Huntington Beach	218	*
Randsburg	115	84

*No calculations available.

Table 2. Principal high-temperature geothermal resource areas in California exclusive of The Geysers and Imperial Valley. Estimated reservoir temperatures and estimated electric energy potential data are U.S.G.S. determinations from Circular 790.

TABLE 4

RESERVOIRS < 90°C (LOW TEMPERATURE)

The following are arbitrarily listed in order of estimated importance as determined by limited information on temperature, flow, and proximity to both population centers and transportation facilities. As most do not have any chemical thermometric data, the reservoirs have been grouped into this low-temperature category by virtue of their maximum measured temperature.

NAME	°C MAX MEASURED TEMPERATURE	COMMENTS
Susanville	53	Several thermal wells in town; potential for district heating (studied by U.S. Bureau of Reclamation).
Paso Robles	43	Potential similar to Susanville except that reservoir temperature may be much lower; being studied by CDMG.
Lower Napa Valley	36	Applications numerous because of population and cultural development; is reservoir hot enough?
Sonoma Valley	46	Several warm wells in a moderately populated area similar to Napa Valley.
San Luis Obispo-Arroyo Grande	57	Several cities in the vicinity of a few known warm wells.
Keough Hot Springs	51	Determined to be a low-temperature reservoir (52°C) by Mariner *et al.* (1977) with a high rate of flow (2,000 lpm). Could have many applications in Bishop, 11 km away.
Santa Barbara-Ojai	56	This area can be split into four small areas, all of which are in the general vicinity of the urban center of Santa Barbara:

Table 4 (continued)

NAME	°C MAX MEASURED TEMPERATURE	COMMENTS
Santa Barbara-Ojai (continued)		San Marcos (43°C), Montecito (48°C), Aqua Caliente (56°C), and Wheeler Springs (51°C). Because each area is within the Transverse Ranges, they may have a common geologic origin.
Brockway Hot Springs	55	Determined to be a low-temperature reservoir (73°C) by Mariner _et al._ (1977), it is situated in the heavily developed north shore area of Lake Tahoe.
Twentynine Palms	63	At least five thermal wells are near the town of Twentynine Palms, which is adjacent to the Marine Corps Training Center.
Imperial Beach	43	Preliminary study by CDMG indicates a low-temperature reservoir in an area that ranges from highly urbanized to rural.
Antelope Valley-Topaz	41	Several small settlements in a valley subject to harsh winters. Along U.S. Highway 395.
Byron Hot Springs	36	Near the small town of Byron in a productive farming and orchard area.
Lake Elsinore Hot Springs	52	Along the Elsinore Fault Zone with some small settlements and major highways; has scientific interest as a site of study of the relationship between strike-slip faulting and thermal springs.
Blythe	45	Many thermal wells just west of the town of Blythe, although it is not known if the temperatures are a result of ambient conditions.
Gilman Hot Springs	47	A group of thermal springs and wells are near several small communities. The thermal activity appears to be associated with the San Jacinto Fault Zone.

Table 4 (continued)

NAME	°C MAX MEASURED TEMPERATURE	COMMENTS
Trona	58	Several wells and a spring are north of this small town. The large chemical industry there could possibly utilize the heat.
Ridgecrest-China Lake	34	Mildly warm wells near these two moderately large communities. It is not clear if the well temperatures are a result of ambient conditions.
Benton Hot Springs	56	Determined to be a low-temperature reservoir (79°C) by Mariner et al. (1977). Near the small settlement of Benton, which has harsh winters.
Octotillo Wells	39	Many mildly warm wells that could be affected by ambient temperatures; near the small settlement of Ocotilo Wells.
Desert Center	35	Several wells that may be affected by ambient temperature; along U.S. Interstate 10.
Paraiso Springs	37	On the edge of a large farming area in the Salinas Valley; somewhat isolated.
Warner Springs	60	Very warm, but very isolated.
Tassajara Hot Springs	62	Extremely isolated in rugged area of the Coast Ranges; has scientific interest because it is one of the hottest springs in the southern Coast Ranges.

TABLE 5

California Energy Commission

Priority Areas of Geothermal

Direct Heat Development

Urban Areas

1. San Diego/Chula Vista
2. Bakersfield and vicinity
3. San Bernardino County (Fontana/San Bernardino)
4. Los Angeles County
5. Orange County
6. Calexico/Mexicali
7. Santa Rosa and environs
8. Riverside County (could move up with proven resource)
9. Santa Clara

Rural Areas

1. Mammoth Lakes Village
2. Bakersfield and vicinity
3. Susanville
4. Paso Robles
5. Ukiah
6. Bishop
7. Santa Rosa and vicinity
8. Lakeport, Kelseyville, Calistoga
9. Napa (Urban and Rural)
10. Lake Tahoe (North)
11. Sierraville
12. Alturas and vicinity
13. Ridgecrest

Other Promising Geothermal Resource Areas

Mt. Shasta and environs
Santa Barbara and vicinity
Salinas/Hollister

Table 5. The above list, compiled by Ms. Syd Willard of the California Energy Commission, identifies potential geothermal areas or sites where a certain need for direct heat applications can be demonstrated. Many, particularly the urban areas, have not previously been regarded as "geothermal" in nature, but contain some evidence of a low-temperature resource.

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V. AREA STUDIES

LOW- AND MODERATE-TEMPERATURE GEOTHERMAL RESOURCES IN MONO BASIN, CALIFORNIA

INTRODUCTION

Mono Basin, situated in central California adjacent to and overlapping the Nevada border (Figure 3), has considerable low-temperature geothermal resources, most of which appear to be confined to its central and southwestern part. Because of the basin's remoteness and because of previous interest in generation of electrical power rather than non-electrical applications, relatively little study of the basin's geothermal resources has been conducted in the past. Nevertheless, numerous geological studies have been conducted in the basin or parts thereof. Among these are the works of Al-Rawi (1969), Chesterman and Gray (1975), Christensen and others (1969), Dunn (1950), Friedman (1968), Gilbert (1938, 1941), Gilbert and others (1968), Kistler (1966a, 1966b), Lajoie (1968), Pakiser and others (1960, 1964), and the classic study of Russell (1889). In addition, Mason (1967) studied the limnology of Mono Lake and Scholl and others (1967) studied its bathymetry. Lee's (1969) work is an excellent source of hydrologic data for the basin. Data for the present report was derived mostly from the reports mentioned above, three days of field work, which involved reconnaissance of the area and checks of properties of some springs, and stereoscopic study of both conventional and infrared aerial photographs which provided supplemental information.

Mono Basin is approximately 1500 km^2 in area and is elongate to the northeast (Figure 4). Mono Lake, a rapidly desiccating saline lake

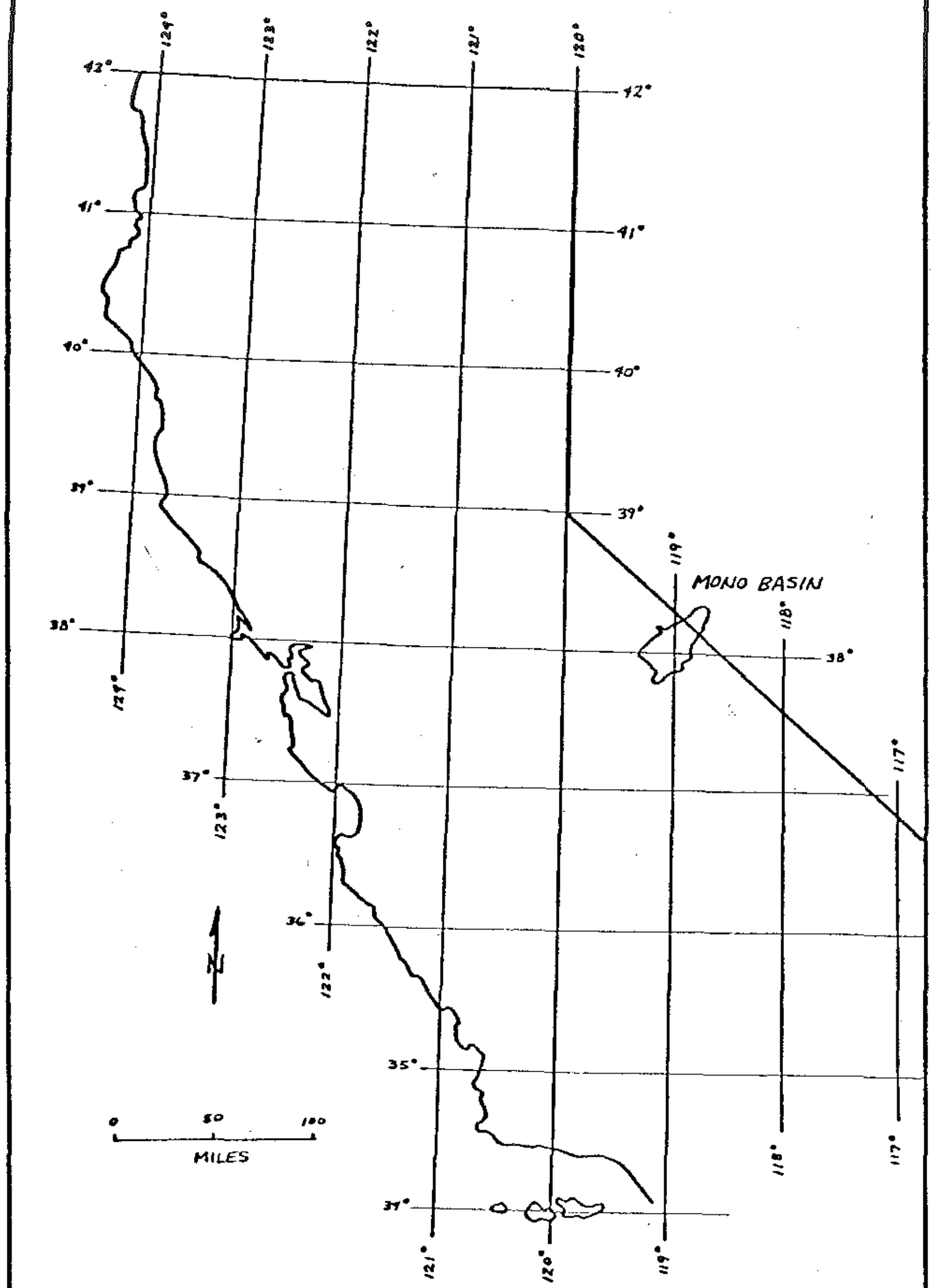


Figure 3 - Location map of Mono Basin.

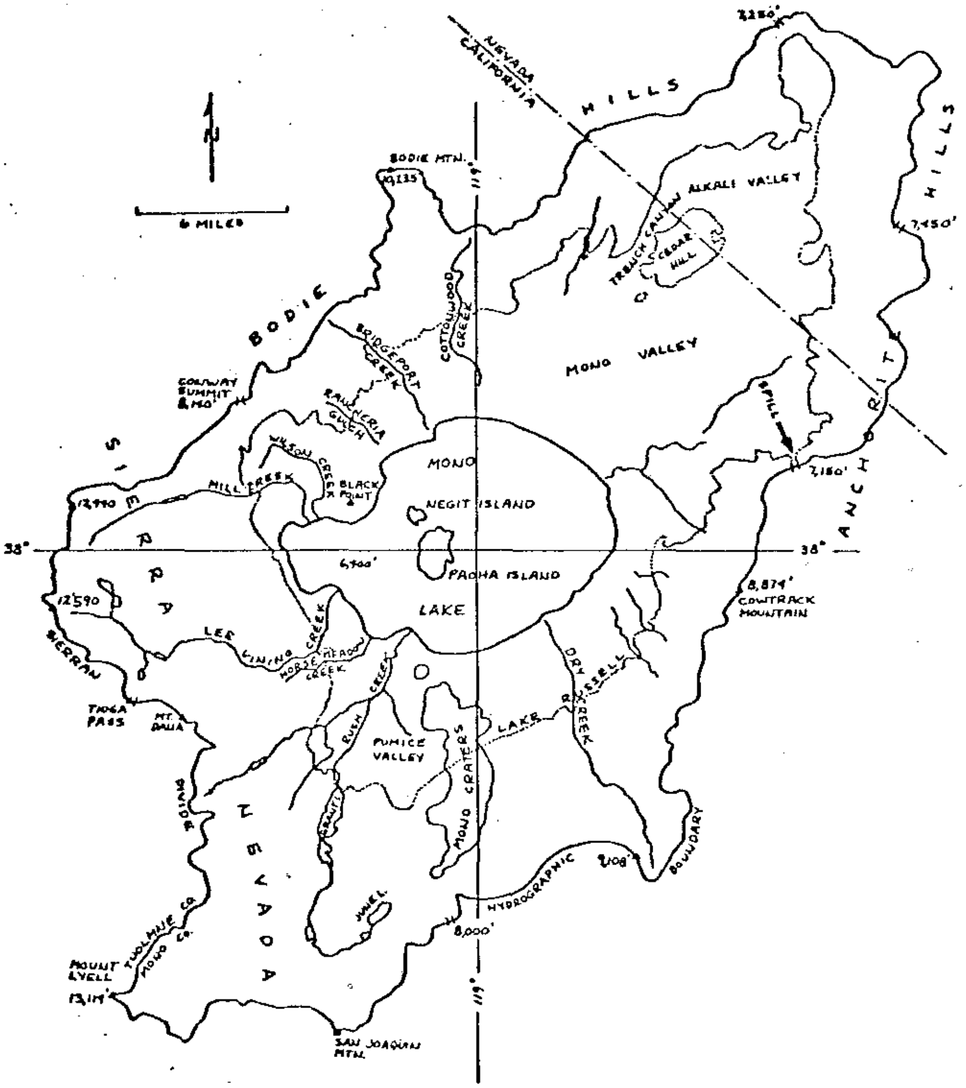


Figure 4 - Geographic features of Mono Basin.

Both figures after Lajoie (1968)

(total dissolved solids equal 94,305 ppm according to Mariner and others, 1977), covers about 180 km^2 of the basin and, in 1968, stood at an elevation of 1,947 m (Lee, 1969). The basin is surrounded by high mountains, the highest of which are at its southwest edge and form the crest of the Sierra Nevada nearly 4,000 meters above sea level. Features of distinctive relief on the floor of the basin include Mono Craters, Black Point, Negit Island, and Paoha Island; otherwise, the floor is gently-sloped.

Zones of vegetation in the basin are mainly dependent on elevation and range from Arctic-Alpine along its southwest rim to Upper Sonoran on its floor. The predominant species in the basin are sagebrush and bitterbrush. Piñon pine and juniper are scattered around the north and east parts of the basin, while pine and fir are extensive in the south part above 2150 meters.

Lee (1969) describes the basin's climate as continental with cold, wet winters and hot, dry summers. The mean annual temperature at Mono Lake is about 9° C, and the precipitation is about 229-305 millimeters (water equivalent), mostly in the form of snow.

STRATIGRAPHY

The mountains that surround Mono Basin are composed of Cenozoic volcanic rocks and pre-Cenozoic plutonic and metamorphic rocks. The latter are confined to the western and southeastern parts of the basin, while the former compose the remainder of the basin (Figure 5). The basin is filled with late Tertiary and Quaternary lacustrine sediments and pumiceous ash, the maximum thinkness of which is probably on the order of 1.5 km as indicated by the logs of two exploratory geothermal

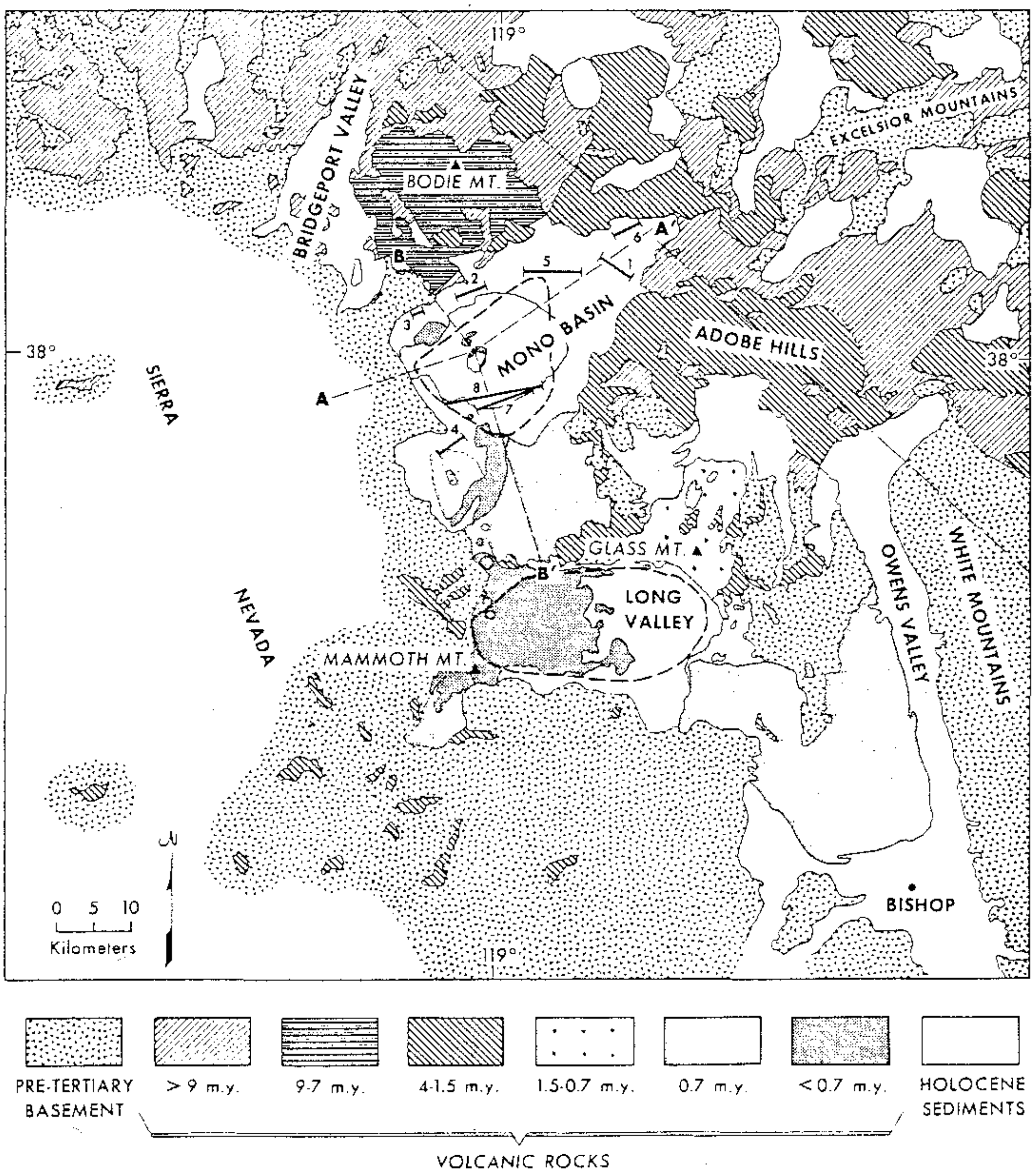


Fig. 5 – Geologic map of the Mono basin vicinity. Rocks are shown by age group; lithology and history are outlined in text. Heavy dashed lines are loci of steep gravity gradients. Numbered bars indicates lines of seismic profiles.

After Christensen and others (1969)

wells on the shores of Mono Lake (Axtell, 1972). Mono Craters, Paoha Island, Negit Island, and Black Point are composed wholly or partly of Holocene or slightly older volcanic rocks.

The oldest rocks in the basin are early Paleozoic metasedimentary rocks of the Log Cabin roof pendant, which is adjacent to the west shore of Mono Lake. The remainder of the metamorphic rocks are metasedimentary and metavolcanic rocks of upper Paleozoic and Jurassic age. The plutonic rocks, which range in age from Jurassic to Cretaceous are more widespread . These are predominantly quartz monzonite with subordinate diorite and gabbro.

According to Christensen and others (1969), at least four separate volcanic terranes of distinct age occur in the basin. The oldest consists of andesite, rhyolite ignimbrite, and latite ignimbrite, and ranges from 9 to 25 million years in age. The other three terranes are summarized in Table 6. The distribution of the volcanic rocks is shown in Figure 5.

The sediments that fill the basin range in age from Pliocene to Holocene and are mostly ashy, diatomaceous lacustrine silts. Lenses of sand and gravel are found at depth, especially in the western part of the basin where there was once abundant glacial and alluvial activity.

STRUCTURE

During the 1960's, two contrasting hypotheses on the structural development of Mono Basin were proposed. The hypothesis of Pakiser and others (1960), essentially an interpretation of seismic and gravity data, states thatthe basin is a volcano-tectonic depression, similar to that of Long Valley, which is just south of Mono Basin. The basin

TABLE 6 – Summary of volcanic history

Approximate Volume, km^3	North and Northeast of Mono Basin	Approximate Age, Years	East and South of Mono Basin	Approximate Volume, km^3
1	Black Point and islands in Mono Lake	Less than 35,000	Mono and Inyo craters	6
	No eruptions	Less than 700,000	Rhyolite, latite, and andesite in Long Valley and Mammoth Mtn.	30*
		700,000	Bishop tuff	300†
		$0.7–1.5 \times 10^6$	Rhyolite of Glass Mountain	20
30	Rhyolite, latite, andesite domes and associated basaltic flows	$1.5–4 \times 10^6$	Olivine basalt flows and cinder cones	65‡
	No eruptions	$4–7 \times 10^6$	*No eruptions*	
35	Andesite and rhyolite near Bodie Mountain	$7–9 \times 10^6$		

Note Table after Christensen and others, 1969

Older volcanic rocks ranging from 9 to about 25 m.y. are distributed over a wide region east, north, and northwest of the Mono basin. They include latite ignimbrite, andesite flows and breccia, and rhyolite ignimbrite; they overlie pre-Tertiary granitic and metamorphic basement rocks.

* Approximate exposed volume; volume buried in Long Valley is unknown and not included.

† Total volume of eruptions centering around Long Valley is estimated at about 300 km^3, but no more than 100 km^3 was emplaced north of Long Valley.

‡ Most of the volume is basalt flows erupted before 3 m.y. ago in the Adobe Hills, east of the Mono Basin; the volume of basalts in the Sierra Nevada and Excelsior Mountains is not included.

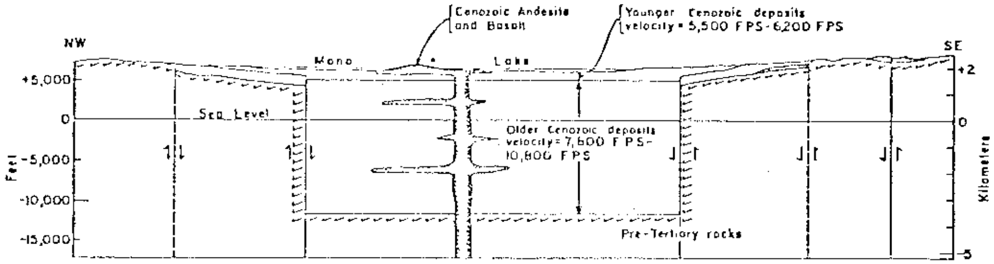
began to subside in the Pliocene along large, steeply-dipping faults as magma was withdrawn from beneath; basin fill consists of both sediments and volcanic flows and has a maximum thickness of about 5.5± 1.5 km. The hypothesis of Gilbert and others (1968) states that the basin is largely a shallow downwarp and is no older than 3-4 million years; fill consists of lacustrine and volcanic sediments of very low density and has a maximum thickness of 1.5 km. Cross sections based on the two hypotheses are shown in Figure 6.

Subsequent to proposal of these hypotheses, two exploratory holes were drilled on the north and south shores of Mono Lake (Axtell, 1972). The lithologic logs of both support the hypothesis of Gilbert and others (1968) that the basin is very shallow and filled with low-density sediments. These holes are discussed more fully below.

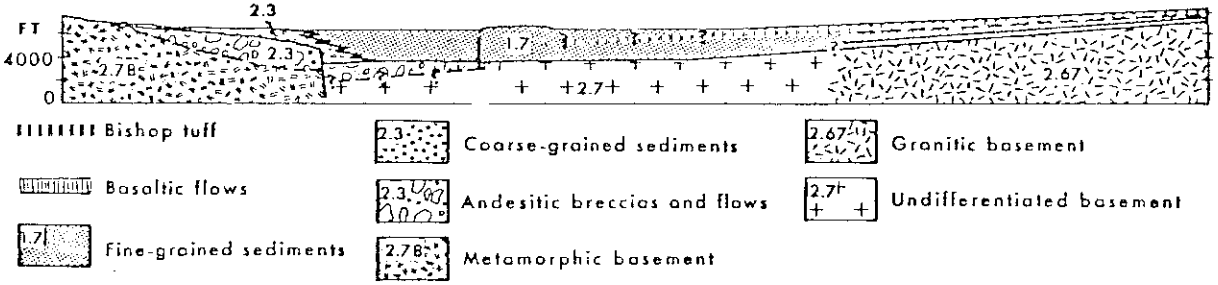
Faults in Mono Basin

Although it appears that the basin is a broad, shallow downwarp, there are numerous faults within the basin, may of which have not been recognized because they lack surface expression. Faults are important because, in many places, they provide conduits for the ascent of thermal waters to the earth's surface. Plate 2 shows recognized and speculated faults in the basin.

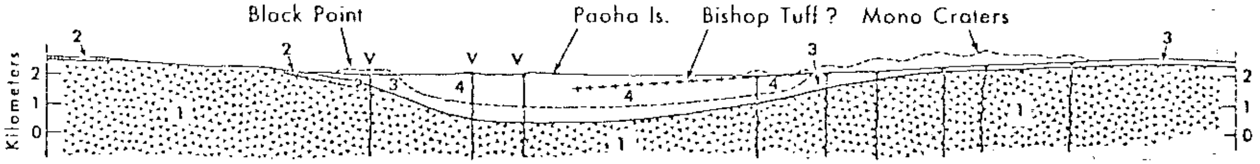
The abrupt rise of the Sierra Nevada west of Mono Lake marks the most prominent fault in Mono Basin. This fault, which has been active mostly during the last 3 million years (Christensen and others, 1969), represents the only structural boundary of the basin formed largely by faulting rather than by downwarping. Its vertical throw near Lee Vining is on the order of a few thousand meters. Curiously, this large northwest-trending fault scarp ends abruptly just south of



a) Interpretation of Pakiser and others, 1960.



b) Interpretation of Gilbert and others, in press.



c) Interpretation of Christensen and others, in press. (1) granitic and metamorphic basement, (2) Miocene volcanic breccias and ignimbrites, (3) alluvial and deltaic gravels and sands, (4) lacustrine silts.

Figure 6 — Structural cross-sections of Mono Basin, NW-SE. (After Lee, 1969)

Lee Vining where it is replaced by a re-entrant into the range-front of the Sierra Nevada. Kistler (1966b) proposed that this re-entrant is caused by subsidence along a ring-fracture zone as shown in Figure 7. Apparently the ring-fracture zone coincides with the protoclastic border of a body of quartz monzonite. Molten material was injected along the eastern border of the zone to form the Mono Craters.

Fault trends in the rest of the basin are either north-northwest or northeast. Movement on most faults appears to be normal dip-slip, but some faults have left-lateral strike-slip motion. The left-lateral faults shown by both Gilbert and others (1968) and by Chesterman and Gray (1975) trend northeasterly.

Several previously unrecognized lineaments, interpreted here to be faults, were discovered from the examination of aerial photographs of the basin (Plate 2). These were recognized mainly from the growth of vegetation along the traces and, in a few cases, from the sudden change from low-lying brush to stands of juniper along a linear boundary. Although numerous cold springs are found along many of these faults, no thermal springs are known to rise along them.

Scholl and others (1967) mapped the bathymetry of Mono Lake and interpreted some of the bottom topography to be a result of faulting. They mention two specific areas: one just east and west of Paoha Island and the other a northeast-trending zone that passes through Negit Island.

The shoreline of Mono Lake is marked by a number of linearly-arranged projections of tufa. These are most common on the south and and east shorelines and several coincide with northerly-trending faults. A prominent offset of the north shoreline in sections 6 and 31, T. 2, 3N,

R. 27E may or may not be result of large-scale faulting. Surface traces were not recognized, but there is a topographic offset of the hills north of the shoreline at Bridgeport Canyon.

The stratiform material that fills the basin is, for the most part, gently-warped and not disturbed by intense folding. Many of the faults in the floor of the basin may have resulted from this warping.

HYDROLOGY

The following is quoted from Bulletin 106-1 of the California Department of Water Resources:

"The principal sources of water supply in the basin are deep penetration of direct rainfall and percolation of stream flow originating in the watershed. Surface waters recharge the ground water basin at a moderate rate through the moraines and alluvial fans fringing the basin."

"Ground water occurs in unconsolidated alluvial deposits, in semiconsolidated older sediments, in glacial moraines, and in fractured volcanic material. Usable ground water supplies are derived from the Recent and underlying older alluvial deposits. The ground water movement is towards Mono Lake, and both free and confined ground water conditions exist."

"The presence of artesian wells in the vicinity of Mono Lake indicates that portions of the water-bearing sediments near the edge of the lake are overlain by relatively fine-grained confining sediments. As a result, much of the ground water in the confined water-bearing sediments apparently discharges into Mono Lake below the surface.

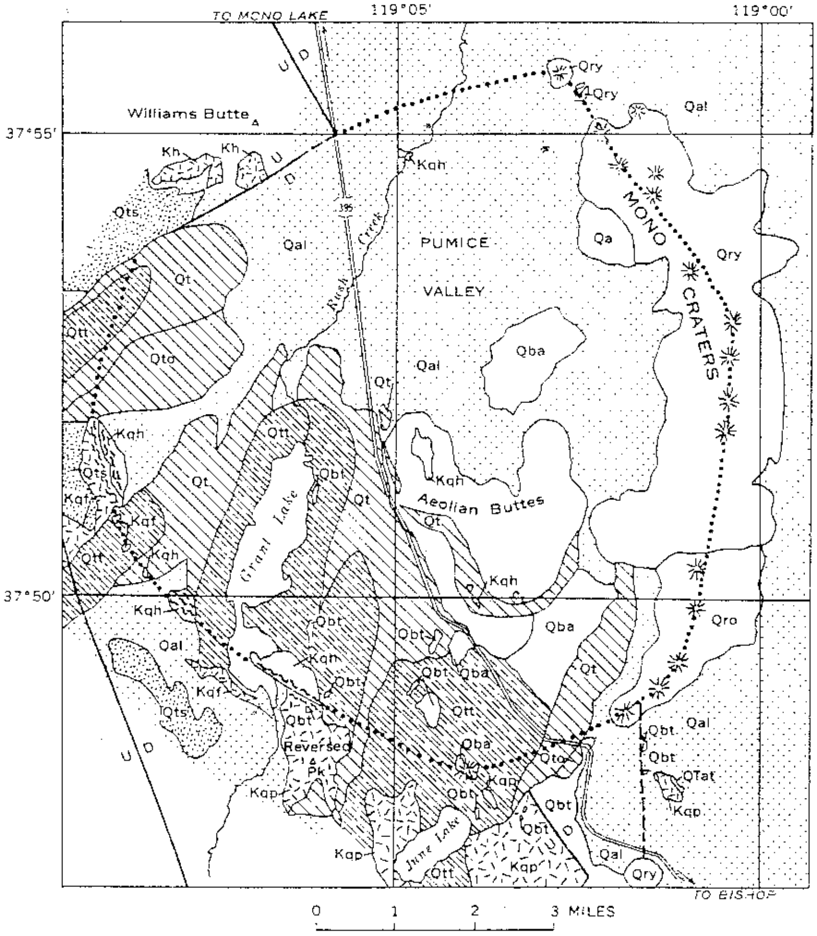


FIGURE 7 – Kistler's (1966b) ring-fracture zone.

Evidence of this discharge is given by fresh water springs which occur within Mono Lake."

"Water levels are at or near the ground surface in wells close to Mono Lake, but depths to ground water may be as much as 300 or 400 feet in the recharge areas along the high alluvial slopes of the basin."

Lee (1969) concluded from drillers' logs of two deep wells in the central part of the basin that there are many confined aquifers which are composed of alluvial sands and gravels separated by confining layers of fine-grained lacustrine silts and ashes. These aquifers are recharged along the margins of the basin floor through fractures in the surrounding igneous rock. Discharge from the aquifers occurs along localized faults as springs and by upward leakage through semi-confining lacustrine sediments.

The hydrologic characteristics of the different rock units in the basin are summarized as follows from data reported by Lee (1969):

Plutonic and Metamorphic Rocks -- These contain insignificant ground water because of a lack of porosity and permeability. Although they are the poorest prospect for water in the basin, some water is available from fault zones as indicated by springs.

Tertiary Volcanic Rocks -- These are not good aquifers, but because of their high permeability in places (joints, faults, breccias, etc.), they are able to conduct water to favorable sites of accumulation. They form zones of recharge on the north, east, and southeast sides of the basin.

Tertiary Sedimentary Rocks -- Of the minor exposures of tuffaceous siltstones, sandstones, and conglomerates, the latter two have good porosity and permeability.

Quaternary Volcanic Rocks -- The Bishop Tuff is thin but widespread in the south part of the basin; although its permeability is low, it can transmit much water because fractures in it tend to remain open at depth. Cinders, of which most of Black Point is composed, have good porosity and permeability, as does the tephra of Mono Craters. During driving of the Mono Craters water tunnel, large flows of water were encountered in several places (Greswell, 1940).

Quaternary Sediments -- Lacustrine deposits are the most widespread material in the basin, while associated alluvial sands and gravels are the best aquifers in the basin. In cases where the sands and gravels underlie the fine-grained lacustrine deposits, artesian conditions are present.

Figure 8 is a map of the hydrologic basin and summarizes the major characteristics of the rocks discussed above.

EVIDENCE OF GEOTHERMAL ACTIVITY

Heat Flow

Lachenbruch and others (1976) recently made three measurements of heat flow in the southern part of Mono Basin (Figure 9), one of which, AB, was near the center of Kistler's (1966b) postulated ring-fracture zone. Its measurement of 2.18 HFU (heat flow units) was normal for this area, while the other two measurements, both east of Mono Craters, were abnormally low at 0.72 HFU (SM) and 0.41 HFU (JM). Lachenbruch and his associates were unable to explain these low quantities and believe they may reflect hydrologic effects.

Seismicity

Seismicity in the Mono Basin for the period 1900-1974 is shown in

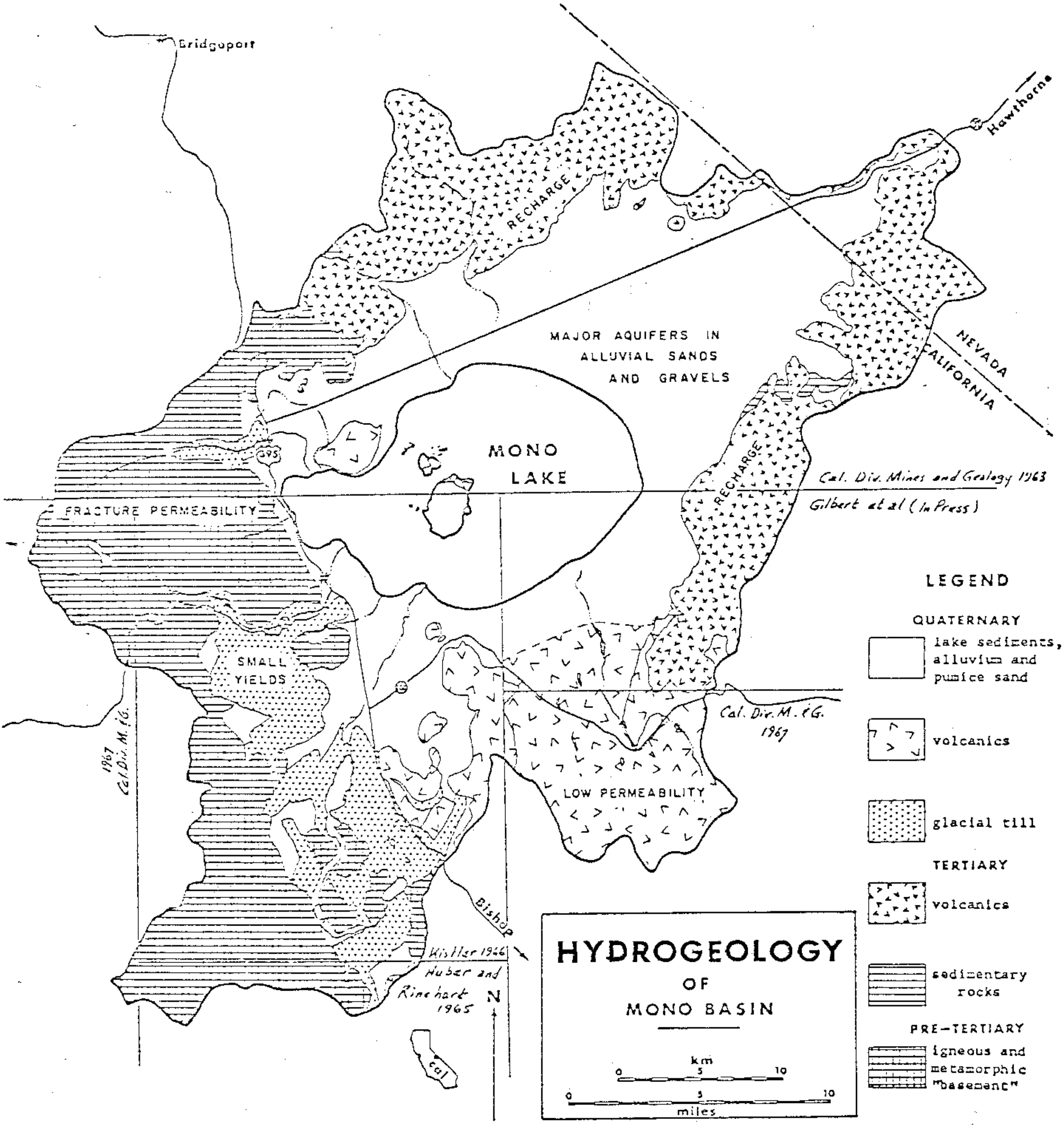


Figure 8 — Hydrogeology of Mono Basin. After Lee (1969).

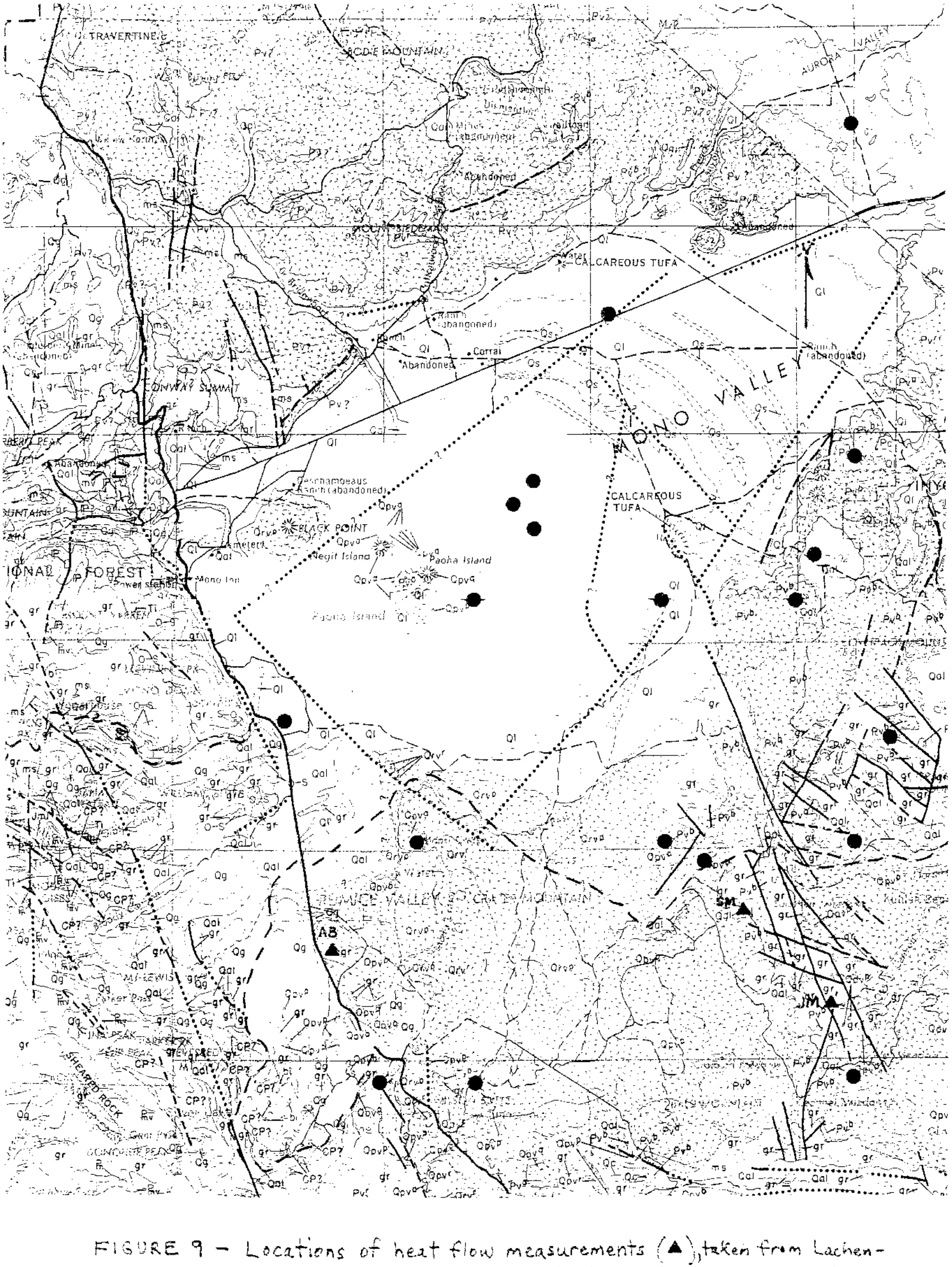


FIGURE 9 - Locations of heat flow measurements (▲), taken from Lachenbruch and others (1976), and epicenters (●) of earthquakes in Mono Basin, taken from Calif. Div. Mines and Geology, 1978. Base map from Calif. Div. Mines and Geology, 1963, 1967. Scale 1:250,000.

Figure 9. Most of the activity was in the eastern and southeastern part of the basin; compared to adjacent areas, the basin had low activity during this time period. This low activity is further documented by data obtained during twenty days of recording of microearthquakes in 1970 by Pitt and Steeples (1975). A plot of their results is shown in Figure 10.

Ryall and Ryall (1979) set up an array of instruments in Mono Basin during the period 1974-1978 and recorded a remarkably concentrated pattern of 269 earthquakes, which is shown in Figure 11. Again, the earthquakes were mostly in the eastern part of the basin. Curiously, during the five years of instrumentation, most of the earthquakes occurred as swarms during the period from July to October of each year. In regard to these swarms, Ryall and Ryall (1979) cited Richin's (1974) work, which stated that swarms of earthquakes appear to be characteristic of seismicity in geothermal areas in Nevada.

Volcanism

Evidence of Quaternary volcanism is extensive throughout Mono Basin. The most recent activity is confined to the western third of the basin where volcanic rocks possibly as young as 1,000 years old are present. A similar situation occurs just to the south in the collapse caldera known as Long Valley, where the youngest volcanic rocks are in the west half of the valley and where a magma chamber is believed to still underlie them at depth (Figure 5).

Except for the basaltic ash and lapilli that compose Black Point, all of the Quaternary volcanic rocks in the western part of the basin are rhyolite or rhyodacite. The numerous craters of Paoha Island,

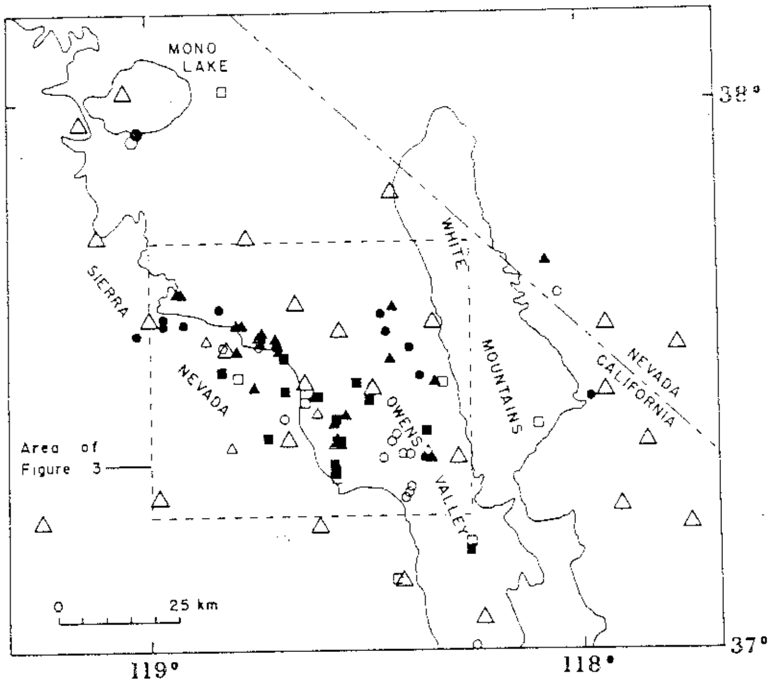


FIG.10-Epicenters of earthquakes located in the present study. Symbol plotted at the epicenter indicates focal depth: circle, 0–5 km; small triangle, 6–10 km; and square, 11–18 km. Solid symbols indicate events with A or B distribution quality which are considered to have more reliable focal depths. The solid hexagon marks the actual location of an explosion in Mono Lake, the open hexagon, the epicenter of the explosion as determined by the hypocenter location program. Seismograph stations are indicated by large open triangles. After Pitt and Steeples (1975).

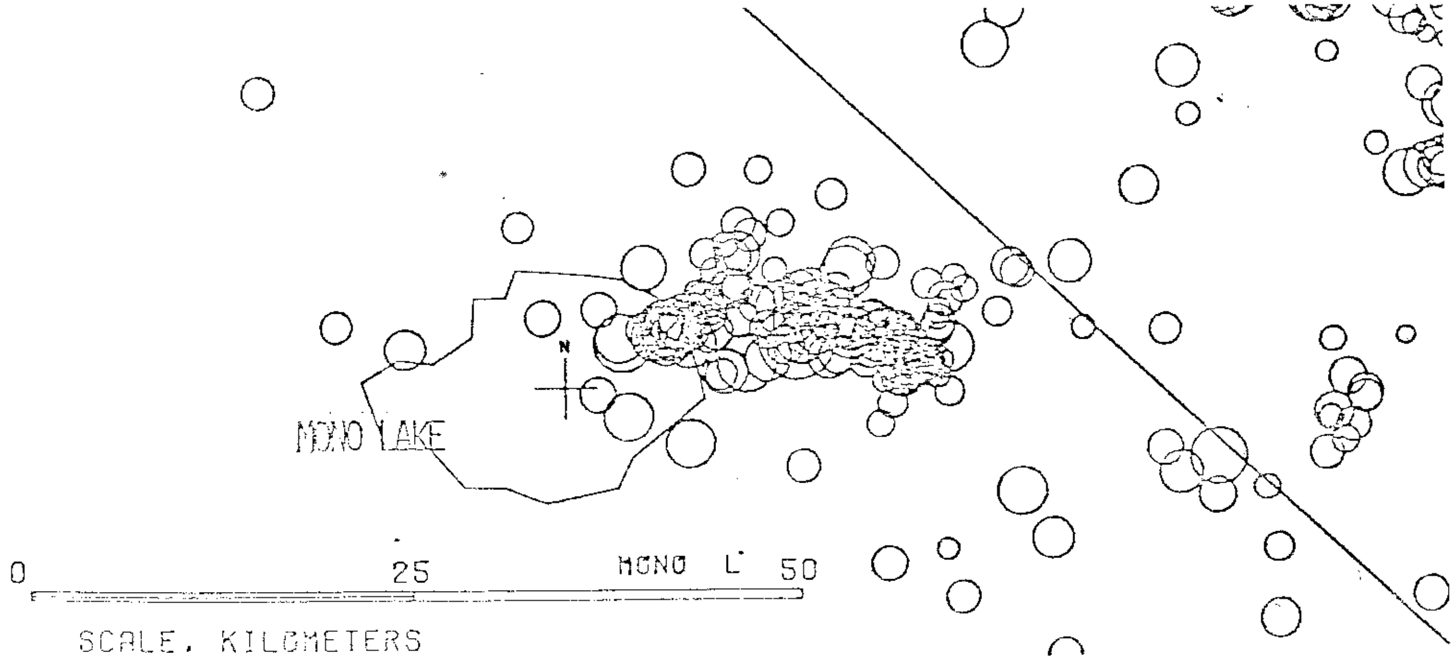


Figure 11 — Earthquakes in the area of the Mina network, for the period June 1974-September 1978. After Ryall and Ryall (1979).

Negit Island, and Mono Craters attest to the explosive nature of this volcanism, while the freshness of the morphology of the plugs, craters, cones, and coulees attests to its young age. Lajoie (1968) reported numerous ages for these rocks ranging from about 1,000 years to about 42,000 years with most of the ages less than 15,000 years (Figure 12). He cites glacial and terrace evidence that suggests an age of less than 3,000 years for the volcanic rocks on Paoha Island. Panum Crater and Northern Coulee may be as young as 1,300 years and 1,800 years, respectively. The recency of this volcanism indicates that magma probably still remains at depth.

The youngest volcanic rocks in the eastern half of the basin, where there are numerous Quaternary faults and earthquake swarms, are about 2 to 4 million years old, as determined by radiometric dating (Al-Rawi, 1969; Christensen and others, 1969).

Thermal Springs and Related Phenomena

As the mean annual air temperature in Mono Basin is only about 9°C, springs with temperatures of 18°C or over are considered here to be thermal. Nearly all of the thermal springs are situated in and around Mono Lake and serve as the best evidence of geothermal activity in the basin.

The hottest and highest volume thermal springs in the basin are on the east shore of Hot Springs Cove, which is on the southeastern shore of Paoha Island. Here, a small peninsula of rhyodacite is cut by many faults, along which waters up to 86°C discharged at a rate of about 380 liters/min in the late 1960's according to Lee (1969). More recently, Mariner and others (1977) measured the temperature as 83°C and estimated the flow as 250 liters/min. C. Forrest Bacon,

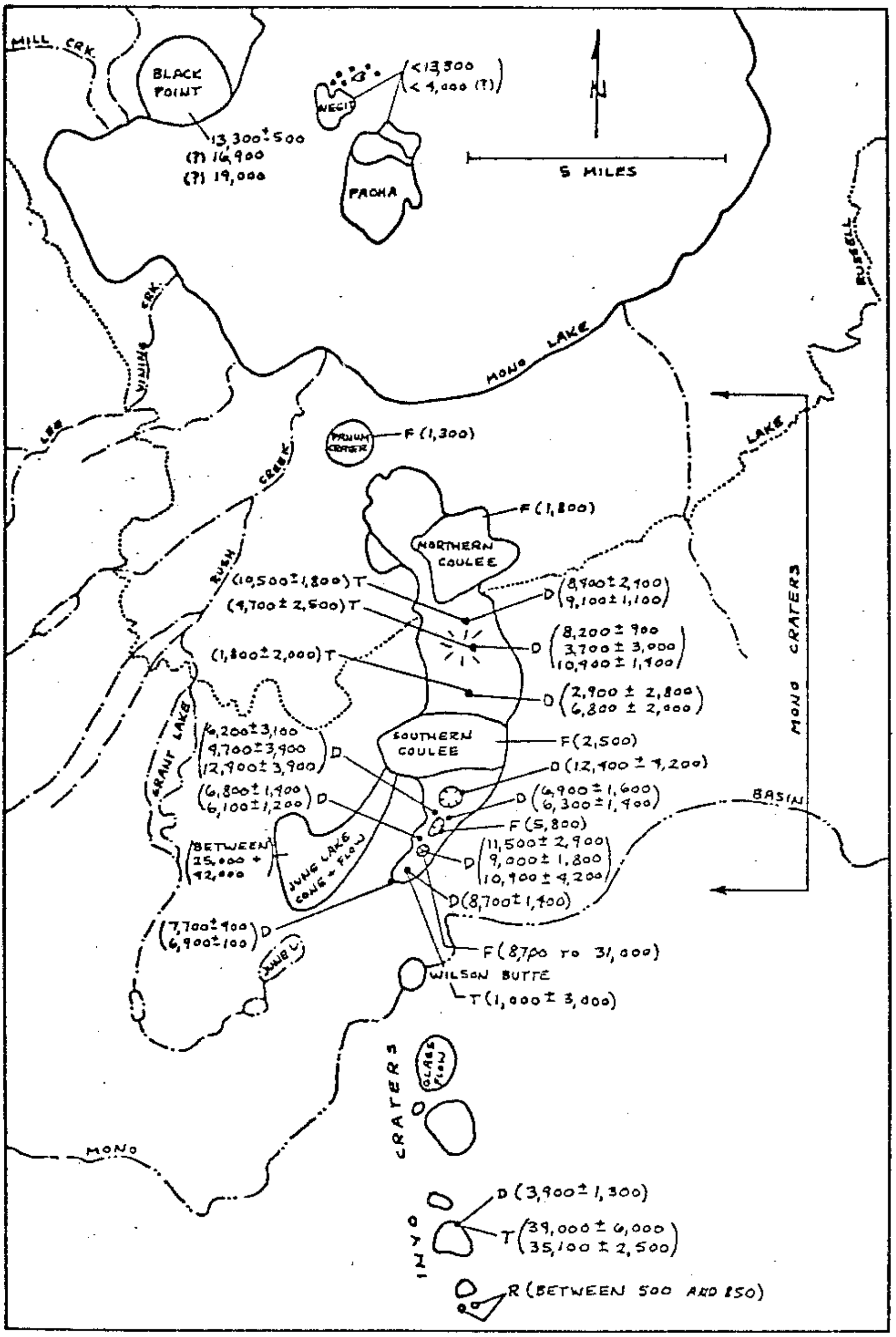


FIGURE 12 – Ages of volcanic rocks in years before present. "D" indicates K/Ar dates, "T" indicates Ionium dates, "F" indicates hydration rind dates, and "R" indicates radiocarbon dates. After Lajoie (1968).

California Division of Mines and Geology, reported (personal communication, 1980) that some springs in this area were boiling in 1972.

Lee (1969) discussed four possible origins of the water at Hot Springs Cove: 1) recycled lake water, 2) deep, confined aquifer, 3) volcanic water, and 4) a combination of these. He eliminated the first possiblity because the chemistry of the thermal springs is different from the chemistry of the water from Mono Lake. Because the chemistry of water from a nearby well on Paoha Island, which taps confined aquifers to a depth of 552 meters, is unlike that of the springs he concluded that the springs are probably not from a confined aquifer. Unfortunately, Lee did not explain why he concluded that a mixture of this deep water and lake water would not produce water similar in composition to the spring water. Because there are no definitive criteria for the recognition of volcanic water, it is difficult to say if these spring waters emanate ultimately from a body of magma. High concentrations of sodium, chloride, fluoride, and boron, often cited as evidence of volcanic water, are characteristic of both the lake water and the thermal spring water. Of possible significance, however, are the <u>percentages</u> of anions in the waters. For example, chloride comprises about 37.5% of the anions in the water of Mono Lake, whereas in samples of two of the thermal springs on Paoha Island, the chloride percentages are 47% and 45%. Except for the Dechambeau well (shown on Plate 2) and a thermal spring in northern Mono Lake, both of which are strongly thermal, these chloride percentages are the highest known in Mono Basin. Lee thus suggested that the spring waters at Paoha Island are a mixture of chloride-rich volcanic water and water from Mono Lake.

Mariner and others (1977) made additional observations of this spring water and concluded that it was a mixture of lake water and thermal water, although they did not know the source of the thermal water. They noted that the spring water is high in mercury and has mostly methane and some nitrogen as gas. Although they admit that their geothermometers are in doubt, they favor a reservoir temperature of only 83°C based on equilibrium of the water with chalcedony. Equilibrium with quartz produces a temperature of 186°C.

Russell (1889) reported a spring on the west shore of Hot Springs Cove with a temperature of 36°C and a discharge of several liters per minute. He also reported fumaroles on the north shore of the cove where steam escaped from openings in the rocks, sometimes in columns of vapor hundreds of feet high. The temperature at the mouth of the principal orifice was 66°C (Russell, 1889). Lee (1969) measured a temperature of 56.0°C here in 1967.

The next-highest temperature springs issue from a tufa tower in the north part of Mono Lake (Plate 2). Lee (1969) measured a temperature of 53.9°C and found that this water had the highest recorded percentage of chloride (60.6%) of any in the basin.

The warm springs on the south and east shores of Mono Lake are characterized by low discharge, the lowest pH of any water in the basin, and high specific conductance (Lee, 1969). The maximum temperature measured by Lee for the southern springs was 41.5°C while that of the eastern springs was 31.4°C. The springs on the south shore have high concentrations of carbon dioxide gas, which is indicative of a high-temperature source according to Mariner and others (1977). They feel that this spring water is a mixture of both lake water and low-temperature water from an aquifer.

The 1950 edition of the U.S. Geological Survey's 30-minute Mt. Morrison topographic quadrangle shows a "hot spring" on the long, north-trending peninsula on the southeast shoreline of the lake (Plate 2). This is the only reference to a thermal spring there; during a field check of this peninsula (now surrounded by land because of desiccation of the lake), no springs with water temperatures above the ambient temperature were observed. The linearity of this former peninsula, which is composed of aligned tufa towers, is probably caused by its formation along a fault. It is conceivable that thermal springs ascended along this fault at one time, but have since been sealed from the thermal source.

Marginally warm waters rise along the west shore of the lake and at the southwest base of Black Point (Plate 2). The former range from 18°C to 22°C, and the latter range from 18°C to 21°C. The maximum flow recorded by Lee (1969) was 464 liters/min, which was from one of the springs along the west shore.

Although he did not discuss specific scamples, Dunn (1953) concluded that there are thermal springs under Mono Lake. Fitch (1927) reported that sometimes many square miles of the lake's surface is covered with vapors, which he believed indicated numerous submersed thermal springs.

Gresswell (1940) reported that carbon dioxide-rich warm springs with temperatures up to 36°C were encountered during driving of the Mono Craters Tunnel. These were associated with a "several-hundred-foot-wide" fracture zone situated about 4,420 meters from the west portal of the tunnel. Gresswell believed that this zone represents a major fissure through which the Mono Craters were probably erupted.

Geochemical and hydrologic data from Mariner and others (1977) and from Lee (1969) are presented in Figure 13 and Tables 7 - 14.

Thermal Wells

Only two thermal wells are known in the basin, excluding the two exploratory geothermal wells drilled in 1971. One is on Paoha Island (Great Western well) and the other is northeast of Black Point (Dechambeau well). Both were artesian when drilled, but only the latter still flows.

The Great Western well was drilled to a total depth of 609 meters in 1908 as an exploratory oil well by the Great Western Oil and Development Company. A driller's log of this well, reproduced from Scholl and others (1967), is shown in Table 15. At 306 meters the water became fresh and at least two and possibly as many as five more aquifers were penetrated. At 519 to 528 meters, the driller reported the water to be quite warm. In 1922, the well flowed at about 60 liters/min of fresh water at about 45°C, but this flow ceased in the mid-1940's (Lee, 1969).

The Dechambeau well was drilled in 1911 to a total depth of 287 meters also as an exploratory hole for oil. According to Lee (1969), the well penetrated at least eight separate confined aquifers, probably sands and gravels separated by fine-grained lacustrine sediments. At 60.7 meters, the well began to flow, and at 79.2 meters very warm water was encountered. As each successive aquifer was penetrated, the water got hotter until at 201 meters the temperature was 57.8°C; evidently no bottom hole temperature was

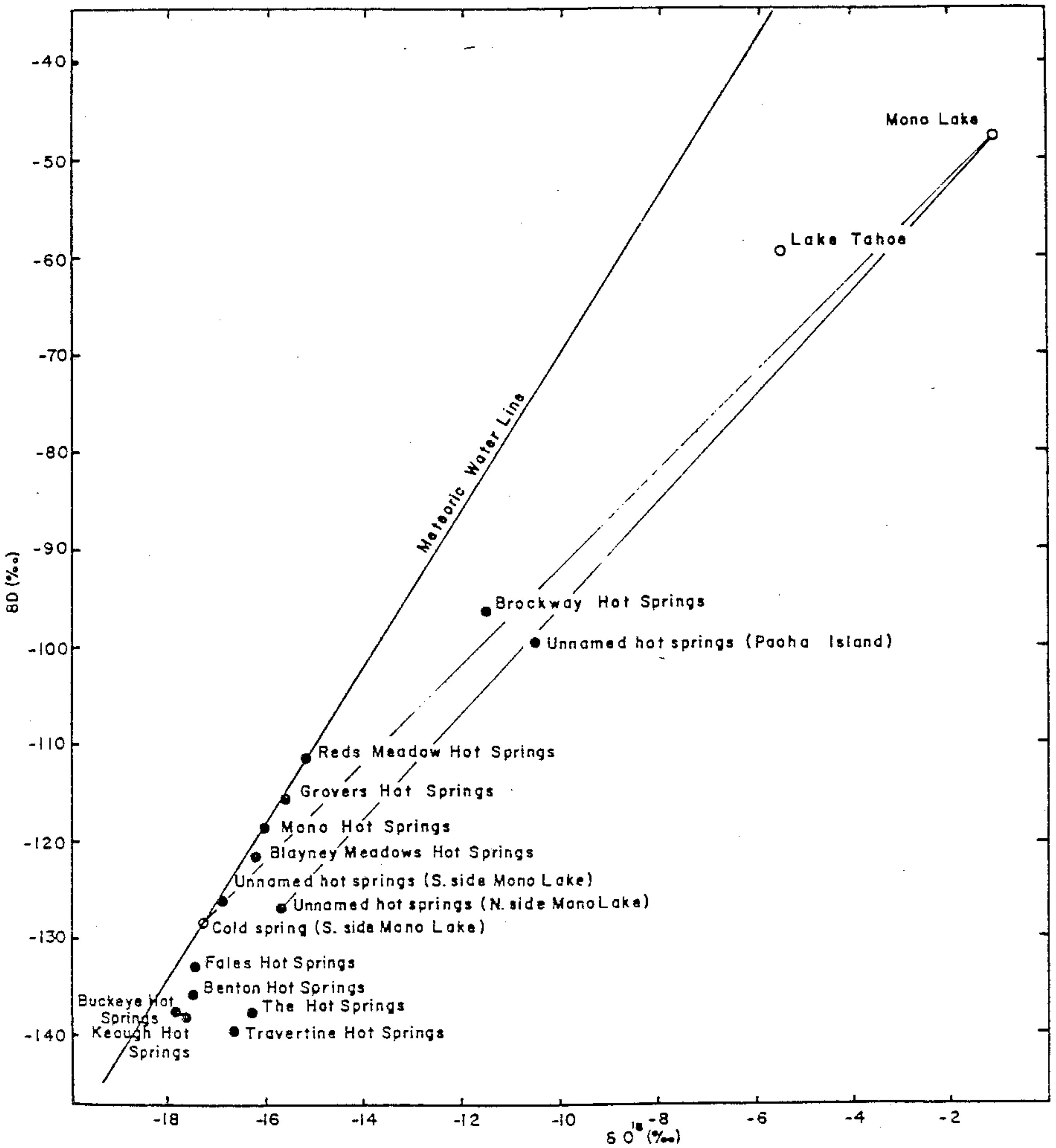


Figure 13 -Plot of δD versus $\delta^{18}O$ in thermal and selected nonthermal waters from the Sierra Nevada. The "tie lines" connecting the compositions of cold and thermal waters around Mono Lake with the composition of water from the lake indicate that the thermal springs on Paoha Island issue a mixture of water of undetermined source and saline water from Mono Lake.

After Mariner and others
(1977).

Table 7 --Location and description of sampled springs

Spring	Location	Description
5. Unnamed hot springs (Paoha Island, Mono Lake)	NW¼sec. 32, T. 2N., R. 27E.	Springs issue along the southeastern shore line of Paoha Island; at least 15 springs; some gas; several springs issue in the lake; flow rate 250 Lpm?
6. Unnamed hot spring (S. Shore, Mono Lake)	E½sec. 18, T. 1N., R. 27E.	Very gassy spring issuing among tufa mounds on the south shore of Mono Lake; flow rate 150 Lpm.
7. Unnamed hot springs (N. Shore, Mono Lake)	E½sec. 11, T. 2N., R. 26E.	Springs are covered and inaccessible; sample from outflow pipe 150 m from source; flow rate 150 Lpm.

Table 8 --Chemical analyses of sampled thermal springs

[Concentrations are in milligrams per liter]

Spring	Temperature (°C)	pH	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Alkalinity as bicarbonate (HCO_3)1/	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Boron (B)	Dissolved constituents2/
Unnamed hot springs (Paoha Island, Mono Lake)	83	9.31	220	.2	<.1	8,000	225	2.5	7,700	2,700	6,000	26	130	26,342
Unnamed hot spring (S. Shore Mono Lake)--	33	6.38	130	120	61	410	34	2.8	1,560	28	105	.4	6.1	2,496
Unnamed hot springs (N. Shore Mono Lake)-	66	7.68	76	13	2.9	430	8.8	.28	454	100	350	4.8	7.7	1,487

1/ Total alkalinity as bicarbonate. Calculated bicarbonate concentrations: Blayney Meadows Hot Springs, 24 mg/L; Keough Hot Springs, 23 mg/L; Benton Hot Springs, 47 mg/L; Unnamed hot springs (Paoha Island, Mono Lake), 7611 mg/L; Unnamed hot springs (N. Shore, Mono Lake), 447 mg/L; Brockway Hot Springs, 54 mg/L.

2/ Dissolved constituents represent the total of all analyzed constituents.

Table 9 --Trace constituent concentrations in thermal waters

[Concentrations are in milligrams per liter; dashes indicate the absence of data]

Spring name	Sulfide (as H_2S)	Aluminum (Al)	Rubidium (Rb)	Ammonia (as N)	Cesium (Cs)	Manganese (Mn)	Copper (Cu)	Nickel (Ni)	Mercury (Hg)	Zinc (Zn)	Iron (Fe)
Unnamed hot springs (Paoha Island, Mono Lake)	38	.005	.95	8.6	.3	<.02	---	---	.024	---	.16
Unnamed hot spring (S. Shore Mono Lake)--	<.5	.003	.04	<.1	<.1	1.7	.06	.03	<.0001	.24	1.4
Unnamed hot springs (N. Shore Mono Lake)-	<.5	.003	.02	3.0	<.1	<.02	.01	<.02	<.0001	.02	<.02

Table 10--Mole ratios of major and minor constituents in the thermal waters

[Dashes indicate that one of the constituents used in the ratio was less than the detection limit.]

Springs	pH	Dissolved solids (mg/L)	Cl/SO_4	Cl/HCO_3	$(F/Cl)x10^2$	$(B/Cl)x10^2$	$(\sqrt{Ca})/Na$	[illegible]	$(Li/Na)x10^3$	$(Mg/Ca)x10^2$
Unnamed hot springs (Paoha Island, Mono Lake)	9.31	26,342	5.8	1.2	.81	7.1	[illegible]	16	1.0	---
Unnamed hot spring (S. Shore Mono Lake)--	6.38	2,491	9.7	.11	.75	20		49	23	77
Unnamed hot springs (N. Shore Mono Lake)--	7.68	1,487	9.5	1.3	2.6	7.2	.96	12	2.2	37

Table 11--Measured spring temperatures and estimated thermal-aquifer temperatures based [illegible] nemical composition of the thermal spring waters

[All temperatures are in °C]

Spring	Spring temperature	Estimated aquifer temperatures for var[illegible] geothermometers[1] Quartz	Chalcedony[2]	Alpha-cristobalite[2]	[illegible]hous[2]	Na-K	Na-K-1/3Ca	Na-K-4/3Ca	Comments
Unnamed hot springs (Paoha Island, Mono Lake)	83	186	84	[illegible]	28	71	---	---	Probable equilibrium with chalcedony at spring temperature.
Unnamed hot spring (S. Shore, Mono Lake)	33	152	12[illegible]	[illegible]9	61	163	170	117	May be a mixed water; geothermometers in doubt.
Unnamed hot spring (N. Shore, Mono Lake)	66	122	[illegible]	73	35	52	124	125	Saturated with calcite; geothermometer in doubt.

[1] Underlined numbers are those favored by the authors.

[2] Adjusted for dissociation of H_4SiO_4 at spring temperature and pH.

Table 12.—Composition of gases issuing from the thermal springs

Spring	Percent by volume O_2+Ar	N_2	CH_4	C_2H_6	CO_2
Unnamed hot springs (Paoha Island, Mono Lake)	1.3	25	70	2.8	.3
Unnamed hot spring (S. Shore, Mono Lake)---	.5	1.3	<.1	<.1	97

---

[1] Detection limits of <0.5 mg/L are for iodometric titrations, whereas detection limits of <1 mg/L indicate that there was hydrogen sulfide at the spring.

From Lee (1969) Outlining or underlining of figures is not pertinent to report.

TABLE 13

HYDROLOGIC FIELD OBSERVATIONS

MONO LAKE FIELD HYDROLOGIC DATA

SPRING OBSERVATIONS

SAMPL	SITE	SOURCE	DATE	TIME	°C TEMP	PH	TYPE	T.D.	WTRDPTH	ELEV	H2S	gpm Q	COMMENTS
[illegible]	[illegible]	SPRG	68 07 31		13.3	7.41	METR					1	
[illegible]	COYOTE	SPRG	68 02 22	0830	8.6	7.10	METR					3	BLM PROJ 595
[illegible]	[illegible]	SPRG	68 02 22	0920	7.8	7.50	METR					1	LOCL UNCONF SEEP
[illegible]	[illegible]	SPRG	68 02 22	1445	10.0	6.50	METR						SEEP
[illegible]	MURPHY	SPRG	68 08 04	1130	13.6	8.40	METR				0.0	10	
													6474.35
	WARFORD	SPRG	68 08 15										
[illegible]	WARFORD	SPRG	69 06 01	1015	11.8	8.2							
	[illegible]	SPRG	67 11 13	0930	8.0	7.29	METR	.	.	6480	-.-	-	POND W/ALGAE
	[illegible]	SPRG	68 08 15										6454.07
[illegible]	BURNHAM	SPRG	68 02 24	1055	16.4	7.85	METR						GN GASTROS
	BURNHAM	SPRG	69 04 25									250	WEIR
[illegible]	[illegible]	SPRG	68 02 22	1030	17.3	7.70	METR					1	
	[illegible]	SPRG	68 09 24										6707.81
	KIRKWOOD	SPRG	69 04 25									17	WEIR
--	[illegible]	SPRG	67 11 13	1155	19.0	8.52	METR	.	.	6395	-.-	2	HUGE SEEP AREA
--	[illegible]	SPRG	67 11 13	1220	10.0	7.98	METR	.	.	6405	-.-	1	ONE OF SEVERAL
[illegible]	[illegible]	SPRG	67 11 13	1310	[illegible]	6.56	METR	.	.	6435	0.0	4	BUBBLY PULSED Q
	[illegible]	SPRG	68 02 21	1330	31.0		METR					20	SAME TEMP AS NOV
	[illegible]	SPRG	68 05 08	1320	31.1								LADWP 53
	[illegible]	SPRG	69 05 24	1550	31.1							20	EST
[illegible]	[illegible]	SPRG	68 02 21	1405	31.5	6.95	METR					20	STRONG BUBBLES
[illegible]	[illegible]	SPRG	68 02 21	1400	31.4		METR						GAS SAMPLE
[illegible]	SAMON	SPRG	67 11 13	1515	12.6	9.70	METR	.	.	6395	-.-	-	LG SEEPS ALNG PT
[illegible]	SESHOR 1	SPRG	68 02 21	1135	12.0	7.40	METR			6393		30	100M SHR
	INDIANSP	SPRG	68 02 21	1950	8.9	9.05	METR			7520		1	LOCL UNCNF SEEP
[illegible]	JAYCREEK	SPRG	68 08 25	1040	8.8	7.11	METR					5	
[illegible]	[illegible]	SPRG	67 11 11	1225	41.5	6.57	METR	.	.		0.0	1	SUBAIR VY FERR
[illegible]	[illegible]	SPRG	67 11 11	1100	35.5	7.10	METR	.	.		0.1	2	SUBLACUSSMPLMIXD
--	[illegible]	SPRG	67 11 11	1200	37.0	6.50	METR	.	.		0.0	1	SUBAIR VY FERR
--	[illegible]	SPRG	67 11 11	1145	[illegible]	-.-	--	.	.		-.-	-	MANYSMALLSPRGS
--	LVDELTA1	SPRG	67 11 12	1625	10.0	7.78	METR	.	.		-.-	5	Q FR T**2 30M SH
--	LVDELTA2	SPRG	67 11 12	1620	9.5	9.13	METR	.	.		-.-	2	PK FE STN
--	LVDELTA3	SPRG	67 11 12	1605	10.5	6.40	METR	.	.		-.-	75	SOLD TSQ 5M SHOR
[illegible]	LVDELTA3	SPRG	68 02 22	1720	10.5	7.50	METR						WTR TT
	LVDELTA3	SPRG	68 05 11		10.0							168	
	LVDELTA3	SPRG	68 05 24		10.0							172	WEIR
	LVDELTA3	SPRG	68 09 27	1700	10.0							188	90 DEG WEIR
	LVDELT 3	SPRG	69 05 22	1530	10.5							236	WEIR
[illegible]	[illegible]	SPRG	67 11 11	1620	13.0	9.49	METR	.	.		0.0	10	TWO SPRGS OF SGP
	[illegible]	SPRG	68 02 22	1605	[illegible]		METR					10	TEMP & Q CHECK
	[illegible]	SPRG	69 05 22	1610	[illegible]							18	WEIR (COMBINED)
[illegible]	[illegible]	SPRG	67 11 11	1645	9.5	9.47	METR	.	.		2.0	1	PK PRCPTH2S ODOR
[illegible]	[illegible]	SPRG	67 11 12	0750	18.0	9.39	METR	.	.		0.0	25	Q AT SHORELINE
--	[illegible]	SPRG	67 11 12	0810	[illegible]	9.16	METR	.	.		-.-	15	Q 5-10M FR SHORE
--	[illegible]	SPRG	67 11 12	0830	10.0	8.98	METR	.	.		-.-	20	VMANY SM SPRGS
[illegible]	[illegible]	SPRG	67 11 12	0845	[illegible]	9.52	METR	.	.		0.0	60	20M SHOR WIDE Q
	[illegible]	SPRG	67 12 24	1120	21.4	9.55	METR			6375		45	TEMP CHECK
	[illegible]	SPRG	68 05 11		22.2							122	WEIR
	[illegible]	SPRG	68 05 25		21.0								
	[illegible]	SPRG	68 12 24	1130	15.6					6389		2	TEMP CHECK [illegible]
--	[illegible]	SPRG	67 11 14	0905	15.0	7.18	METR	.	.		2.0	2	SHOR H2S ODOR
--	[illegible]	SPRG	67 11 14	0735	.	.	METR	.	.		.-	1	SEV SEEPS
--	[illegible]	SPRG	67 11 14	0815	.	.	METR	.	.		.-	-	SEEP IN FOSSSOIL
--	[illegible]	SPRG	67 11 14	0825	.	.	METR	.	.		.-	1	SPG TOP TT (ARTI
--	[illegible]	SPRG	67 11 14	0840	15.7	8.40	METR	.	.		.-	4	SPG W/ALG BRUSH
--	[illegible]	SPRG	67 11 14	0855	16.1	8.82	METR	.	.		.-	30	SEV SPRGS 5-20M
--	[illegible]	SPRG	67 11 14	0905	7.8	7.40	METR	.	.		.-	50	MULTI SPGS
--	[illegible]	SPRG	67 11 14	0955	9.7	8.74	METR	.	.		.-	-	VY LG SEEP AREA

TABLE 13 - Continued

SMPL	SITE	SOURCE	DATE	TIME	TEMP	PH	TYPE	T.D.	DEPTH ELEV	H2S	Q	COMMENTS
	MUNUVISA	SPRG	67 11 14	1210	9.4	7.63	METH	.	.	.-		LG TT NEAR [illegible]
312	MUNUVISA	SPRG	[illegible]	0940	9.7	7.35	METH					
	MUNUVISA	SPRG	[illegible]									0.72 6M VENT
	MUNUVISA	SPRG	[illegible]									
	MUNUVISB	SPRG	67 11 14	1220	9.8	7.45	METH	.	.	.-		SM TT
	MUNUVISB	SPRG	[illegible]		10.6						819	WEIR
	MUNUVISB	SPRG	[illegible]		12.5						198	WEIR
	MUNUVISB	SPRG	[illegible]		11.1						483	WEIR
	MUNUVISB	SPRG	[illegible]		11.1						310	WEIR
	MUNUVISB	SPRG	[illegible]	0905	11.1						447	90 DEG WEIR
	MUNUVISB	SPRG	[illegible]								378	WEIR
	MUNUVISC	SPRG	[illegible]		13.3						73	BUCKT 225UM [illegible]
	MUNUVISC	SPRG	[illegible]		12.2						90	WEIR
	MUNUVISC	SPRG	[illegible]	1525	12.2						110	90 DEG WEIR
	MUNUVISD	SPRG	[illegible]		16.1						7	BUCKT 8
	MUNUVISD	SPRG	[illegible]		11.7						21	WEIR
	MUNUVISD	SPRG	[illegible]		13.3						27	WEIR
	MUNUVISD	SPRG	[illegible]	1535	13.3						22	90 DEG WEIR
	MUNUVISH	SPRG	[illegible]								2	
	MUNUVISI	SPRG	[illegible]								2	
	MUNUVISJ	SPRG	[illegible]								91	WEIR
	MUNUVISK	SPRG	[illegible]		12.2						22	WEIR
	MUNUVISL	SPRG	[illegible]		13.3						552	WEIR
	MUNUVISL	SPRG	[illegible]		15.3						540	WEIR
	MUNUVISL	SPRG	[illegible]	1015	12.2						847	90 DEG WEIR
	MUNUVISL	SPRG	[illegible]								680	WEIR
411	MUNUVISM	SPRG	[illegible]		11.1	8.21	METH				28	WEIR
	MUNUVISM	SPRG	[illegible]		16.1						37	WEIR
	MUNUVISM	SPRG	[illegible]	1100	15.0						52	90 DEG WEIR
	MUNUVISN	SPRG	[illegible]								10	
	MUNUVISN	SPRG	[illegible]		17.2						60	
	MUNUVISN	SPRG	[illegible]		15.5						240	WEIR
	MUNUVISN	SPRG	[illegible]	1120	17.6						278	90 DEG WEIR
	MUNUVISN	SPRG	[illegible]								156	WEIR
	MUNUVISP	SPRG	[illegible]								12	
	MUNUVISQ	SPRG	[illegible]		10.0						9	
	MUNUVISR	SPRG	[illegible]								11	
	MUNUVISS	SPRG	[illegible]		10.0						60	WEIR
	MUNUVISS	SPRG	[illegible]		9.4						65	WEIR
	MUNUVIST	SPRG	[illegible]								15	
	MUNUVISU	SPRG	[illegible]		13.9						14	
	MUNUVISX	SPRG	[illegible]		11.5						1120	CIR WEIR AT LAKE
401	MV SUB 1	SPRG	[illegible]	0915	9.6				0.5			9.58
	MV SUB 1	SPRG	[illegible]	0930	9.4				20.0			
	MV SUB 1	SPRG	[illegible]	0935	9.4				50.0			
	MV SUB 1	SPRG	[illegible]	0940	11.4				56.0			V SOFT BOTTOM
404	MV SUB 4	SPRG	[illegible]	1430								9.05
	MV SUB 4	SPRG	[illegible]	1440	10.5				20.			
	MV SUB 4	SPRG	[illegible]	1450	9.2				31.			HD RUF BOTTOM
317	MV SUB 6	SPRG	[illegible]	1400	13.9							PROB MIXD W/LAKE
40-	MV SUB 7	SPRG	[illegible]	1030	10.4				0.5			6.56 NEW [illegible]
	MV SUB 7	SPRG	[illegible]	1045	9.9				20.			
	MV SUB 7	SPRG	[illegible]	1100	10.1				50.			
	MV SUB 7	SPRG	[illegible]	1110	10.4				67.5			V SOFT BOTTOM
--	BLKPT 1	SPRG	67 11 14	1415	10.4	7.64	METH	.	.	.-	100	TT SPLITS GARDEN
--	BLKPT 2	SPRG	67 11 14	1440	10.4	7.90	METH	.	.	.-	80	TT AT SHORE
--	BLKPT 3	SPRG	67 11 14	1445	.	.	METH	.	.	.-	50	Q INTO LAKE
--	BLKPT 4	SPRG	67 11 14	1450	.	.	METH	.	.	.-	35	Q INTO LAKE
--	BLKPT 5	SPRG	67 11 14	1455	.	.	METH	.	.	.-	5	Q INTO LAKE
--	BLKPT 6	SPRG	67 11 14	1505	9.5	8.16	METH	.	.	.-	150	Q INTO LAKE
--	BLKPT 7	SPRG	67 11 14	1510	.	.	METH	.	.	.-	10	Q INTO LAKE

TABLE 13 - Continued

SMPL	SITE	SOURCE	DATE	TIME	TEMP	PH	TYPE	T.D.	WIRDPTH ELEV	H2S	Q	COMMENTS
	BK PT A	SPRG	67 11 14	1525	9.8	8.04	METR	.	.	.-	40	TT SH MIER WILCK
314	BK PT A	SPRG	68 02 23	1225	10.4	8.05	METR				41	
	BK PT A	SPRG	68 05 09		10.6						65	
	BK PT A	SPRG	68 06 22		10.3						63	WEIR
	BK PT A	SPRG	68 08 30	0915	10.6						50	WEIR
	BK PT A	SPRG	69 05 30								70	WEIR
	BK PT B	SPRG	68 05 09		10.6						66	
	BK PT B	SPRG	68 06 22		10.6						55	WEIR
	BK PT B	SPRG	68 08 30	0940	10.8						63	WEIR
	BK PT B	SPRG	69 05 30								65	WEIR
	BK PT C	SPRG	68 05 09		14.4						16	16 SEEP
	BK PT D	SPRG	68 05 09		10.0						25	26
	BK PT D	SPRG	69 05 30								28	WEIR
	BK PT E	SPRG	68 05 09		20.0						2	2 SEEP
	BK PT F	SPRG	68 05 09		16.1						5	5 SEEP
	BK PT G	SPRG	68 05 09		10.0						3	2
	BK PT H	SPRG	68 05 09		12.2						51	PT SEEP
	BK PT I	SPRG	68 05 09		16.1						163	
	BK PT I	SPRG	68 06 22		14.4						140	WEIR
	BK PT I	SPRG	68 08 30	1000	13.5						139	WEIR
	BK PT I	SPRG	69 05 30								156	WEIR
	BK PT J	SPRG	68 05 09		19.4						19	19 SEEP
	BK PT K	SPRG	68 05 09		13.3						31	33
	BK PT K	SPRG	69 05 30								142	WEIR
	BK PT L	SPRG	68 05 09		20.6						7	7 SEEP
	BK PT M	SPRG	68 05 09		20.[illegible]						53	SEEP
	BK PT M	SPRG	68 06 22		20.[illegible]						53	WEIR
	BK PT M	SPRG	68 08 30	1035	13.5						32	WEIR
	BK PT N	SPRG	68 05 09		11.1						123	
	BK PT N	SPRG	68 08 30	1135	11.2						193	WEIR
	BK PT O	SPRG	68 05 09								5	
	BK PT P	SPRG	68 05 09		11.7						167	
	BK PT P	SPRG	68 06 22		13.3						180	WEIR
	BK PT P	SPRG	68 08 30	1205	15.9						182	WEIR
	BK PT Q	SPRG	68 05 09		11.1						75	
	BK PT R	SPRG	68 05 09		12.2						16	
	BK PT S	SPRG	68 05 09		12.8						2	
	BK PT T	SPRG	68 05 09		12.8						24	
	BK PT T	SPRG	68 06 22		19.4						19	WEIR
	BK PT T	SPRG	68 08 30	1235	18.2						5	WEIR
	BK PT U	SPRG	68 05 09		11.7						30	
405	BP TT 1	SPRG	68 05 07	0820	11.4	8.58	METR				40	QMOST S&SW LK+15
	BP TT 2	SPRG	68 05 07	0900							20	MOST ON SOUTH
406	BP TT 3	SPRG	68 05 07	0915	10.4	9.64	METR				12	SM RD TT W/ HOLE
407	BP TT 4	SPRG	68 05 07	0935	11.3							6.58 LGSURQ ON N
402	BP TT 5	SPRG	68 05 05	1200	10.9	8.49	METR		.3			3.58 SMPL MIXD ?
501	SODA TT	SPRG	68 06 21		53.9	7.80						
512	PAUHA [illegible]	SPRG	68 06 21		75.6							SLOT
507	PAUHA [illegible]	SPRG	68 08 02	1505	78.3	8.96	METR			5.0	20	SLOT
	PAUHA [illegible]	SPRG	68 06 21		85.6							E SIDE ARMY DOCK
506	PAUHA 3	SPRG	68 08 02	1330	7.8	9.30	METR			5.0	10	COLD SPRING
	PAUHA 4	SPRG	68 08 02		9.4						2	
503	PAUHA 5	SPRG	68 08 02	1600	21.5	6.78	METR			0.0	30	SURF RUNOFF
--	CRATERMTN	FUM	67 11 11	0925	56.0	-.-	--	. .	.	0.0	-	STEAMING SULPH?

TABLE 13 - Continued

[illegible] LAKE FIELD HYDROLOGIC DATA

ALL OBSERVATIONS

SMPL	SITE	SOURCE	DATE	TIME	TEMP	PH	TYPE	T.C.	WTRDPTH	ELEV	H2S	Q gpm	COMMENTS
213	[illegible]	WELL	67 11 12	1400	65.5	7.10	METR	.	.		0.0	60	MUCH FE STN
	MARGREEN	WELL	68 05 08	1055				7.6	7.19				LADWP 61
	MARGREEN	WELL	69 05 02						5.10				
604	[illegible]	WELL	69 05 28	1025	15.0	7.01			7.01				
	WAN 1	WELL	68 08 15						24.37				REF CSNG [illegible]
	WAN 1	WELL	69 05 24	1220					23.97				
[illegible]	WAN 2	WELL	68 06 08		15.7	9.82	METR				0.0		
	WAN 2	WELL	68 08 15						1.91				REF CANS [illegible]
[illegible]	WAN 3	WELL	68 08 15						2.06				REF CANS [illegible]
	WAN 4	WELL	68 08 15						1.71				REF CANS 6397.[illegible]
	WAN 5	WELL	68 08 15						1.96				REF CANS [illegible]
	WAN 6	WELL	68 08 15						1.69				REF GRND 6391.[illegible]
	WAN 7	WELL	68 08 15						.53				REF GRND [illegible]
	WAN 8	WELL	68 08 15						4.45				REF GRND [illegible]
	WAN 9	WELL	68 08 15						5.25				REF GRND [illegible]
	WAN10	WELL	68 08 15					14.2					REF CSNG [illegible]
	WAN 11	WELL	68 09 04						-.52				REF CAN [illegible]
	WAN12	WELL	68 09 04										
	HIGHWAYS	WELL	68 09 03					55.2					REF BEAM [illegible]
	HIGHWAYS	WELL	68 09 03					125.4	37.60				REF12"CSG[illegible]
[illegible]	HIGHWAYS	WELL	69 05 25	0945	15.5	8.46			37.14				
[illegible]	[illegible]	WELL	[illegible]	1035	12.4	8.77	METR	[illegible]	[illegible]		[illegible]	2	[illegible]
	[illegible]	WELL	[illegible]						[illegible]				REF CSG [illegible]
	ANNADIAS	WELL	[illegible]	1640	11.4				[illegible]				[illegible]
	ANNADIAS	WELL	[illegible]	1015				25.5	15.93				LADWP 60
505	ANNADIAS	WELL	[illegible]		16.4				14.1[illegible]			1	
	ANNADIAS	WELL	[illegible]						[illegible]				REF[illegible]CSG [illegible]
	ANNADIAS	WELL	[illegible]						12.35				
	NETTAULT	WELL	[illegible] 24	1420	12.7	7.75	METR	49.5	[illegible]			[illegible]	12.4 AT [illegible]
	NETTAULT	WELL	[illegible]	1120				49.	[illegible]				LADWP 54
[illegible]	NETTAULT	WELL	[illegible]		16.0	7.94						2	
	NETTAULT	WELL	[illegible]						[illegible]				REF CSG [illegible]
	NETTAULT	WELL	[illegible]						[illegible]				
	THOMAULT	WELL	[illegible]	1457	12.6	[illegible]	METR		[illegible]			[illegible]	H2S [illegible]/ARTESIAN
	THOMAULT	WELL	[illegible]	[illegible]				54.9	.41				LADWP [illegible]
[illegible]	THOMAULT	WELL	[illegible]		14.2	8.43						18	
	THOMAULT	WELL	[illegible]						1.02				REF BEAM [illegible]
	THOMAULT	WELL	[illegible]						-[illegible]				
	THOMAULT	WELL	[illegible] 24	1240	13.5								FLOWING [illegible]
214	[illegible]	WELL	67 11 12	1025	13.0	9.57	METR	.	- 3.	643[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	WELL	[illegible]	1522	13.1	8.80	METR		-3.	[illegible]		17	ARTESIAN WELL
	[illegible]	WELL	[illegible]	[illegible]	12.9			76.	[illegible]				LADWP [illegible]
	[illegible]	WELL	[illegible]						2.94				REF CSG [illegible]
	[illegible]	WELL	[illegible]						-12.32			[illegible]	[illegible]

TABLE 13 – Continued

SMPL	SITE	SOURCE	DATE	TIME	TEMP	PH	TYPE	T.D.	WTRDPTH	ELEV	H2S	Q	COMMENTS
	CLOVER 2	WELL	68 02 24	1548	12.2	8.15	METR	19.0	14.15	6434		0	12.2 AT 14FT
	CLOVER 2	WELL	68 05 28	1210				19.	13.92				LADWP 57
	CLOVER 2	WELL	68 09 03					19.0	14.52				REF CSG 6427.50
	CLOVER2T	WELL	69 05 02						-12.32				
	CLOVER 3	WELL	68 02 24	1610				10.9		6434		0	DRY TAG?SPM
	CLOVER 3	WELL	68 05 28	1205				10.9					LADWP 58 DRY
	CLOVER 3	WELL	68 09 03					10.8					REF CSG 6427.98
	CLOVER3N	WELL	69 05 02						-19.14				
	ALAMEDA	WELL	68 08 06					92.2					DRY
509	TYREETOO	WELL	68 02 22	1210	16.9	7.20	METR	268.	239.	6730			PUMPED 30 MIN
522	TYREETOO	WELL	68 05 19	1810	17.6	7.51					0.0		PUMPED 7 HOURS
504	TYREE217	WELL	68 02 21	1450	13.2	9.55	METR			6520			WINDMILL PUMP 20
415	TYREE217	WELL	68 05 19	1530	13.3	9.41							PUMPED 6 HOURS
	AWE 1	WELL	68 08 14						.79				REF CANS 6391.20
	AWE 2	WELL	68 08 14						1.36				REF CANS 6394.30
	AWE 3	WELL	68 08 14						1.35				REF CANS 6397.15
	AWE 4	WELL	68 08 14						2.00				REF CANS 6398.15
	AWE 5	WELL	68 08 14						1.92				REF CANS 6399.65
	AWE 6	WELL	68 08 14						1.38				REF CANS 6405.72
514	AWE 7	WELL	68 08 14	1320	22.5	8.73	METR		2.70				REF CANS 6407.78
	AWE 8	WELL	68 08 14						4.94				REF CSNG 6422.30
	AWE 8	WELL	69 05 24	1405	10.8				2.95				
	AWE 9	WELL	68 08 14						11.70				REF CSNG 6432.21
513	AWE10	WELL	68 08 14		11.4	9.09	METR		3.68				REF CSG 6438.01
	AWE10	WELL	69 05 24	1450	10.2				3.85				
515	AIRWELL1	WELL	68 02 24	1310	11.4	7.60	METR	9.9	5.25			0	11.0 AT 5.3FT
	AWE11	WELL	68 08 14						6.46				REF CSNG 6439.59
	WS TEST1	WELL	68 05 28	1300									LADWP 66 DRY
	WS TEST2	WELL	68 05 28	1305									LADWP 67 DRY
	WS TEST3	WELL	68 05 28	1310									LADWP 68 DRY
	AWS 1	WELL	68 09 05						4.47				REF GRND 6392.74
	AWS 2	WELL	68 09 05						12.55				REF CSG 6401.36
	AWS 2	WELL	69 05 24						10.45				
517	[illegible]	WELL	67 10 09	1100	14.0								ABT 30M FR LAKE
403	CAINRNCH	WELL	68 05 05	1425	10.5	7.73	METR						
404	[illegible]	WELL	68 05 05	1530		7.75	METR						FROM STORAG TANK
502	KELLY'S	WELL	69 05 24	1612	11.8	7.21			1.7				V LO PERM
501	PAOHA	WELL	69 05 24	1230	19.5	7.5			21.5	6472			

TABLE 14 Chemical Analyses of Mono Basin Waters (After Lee, 1969).

Outlining or underlining of figures is not pertinent to report.

LABORATORY ANALYSES OF WATER SAMPLES FROM
MONO LAKE, CALIFORNIA

SAMPLES 201 THROUGH 402

NO.	SAMPLE SITE	SOURCE	SAMPLE DATE	TEMP °C	PH	DISCHARGE gpm	ANALYSIS DATE	SIO2	NA	K	CA	MG	FE	B ppm	CO3	HCO3	CL	SO4	F	NO3	H2S	SPEC COND	TDS	EPM CATION	EPM ANION	EPM % IMBALANCE	NO.
201	HOTSPG 2	SPRG	671111	86.5	7.10	2	671221	92.0	700.0	46.0	112.0	24.0	0.2	0.0	0.0	1610.4	190.5	128.0	1.8	3.0	0.1	3223	2077	39.19	34.35	6.6	201
202	MONO LKE	LAKE	670918	19.4	10.00	6	671016	2.5	26400.0	1240.0	0.0	45.6	0.6	470.5	14160.0	5857.0	17211.0	11500.0	45.0	0.0	0.0	123980	75937	1270.87	1294.46	-0.9	202
203	HOTSPG 1	SPRG	671111	41.5	6.57	1	671221	97.0	510.0	43.0	180.0	38.4	0.1	4.2	0.0	1830.0	85.0	44.0	1.1	7.5	0.0	2851	1914	35.42	33.57	2.7	203
204	RUSH CRK	SURF	671111	11.0	6.98	27000	671221	10.0	1.8	1.0	7.0	2.4	0.0	0.0	0.0	36.5	1.7	4.5	0.0	0.0	-0.0	47	44	0.60	0.72	-8.8	204
205	LVCK DAM	SURF	671111	5.0	7.44	400	671221	11.0	3.0	1.2	7.4	0.0	0.0	0.0	0.0	14.6	1.0	2.6	1.0	0.0	-0.0	35	31	0.48	0.31	21.6	205
206	CHARC 11	SPRG	671111	11.0	9.49	10	671221	27.0	64.0	2.9	2.4	1.0	0.0	0.3	24.0	85.4	6.9	19.0	0.0	0.4	1.0	331	189	3.06	2.80	4.4	206
207	NSHORE 1	SPRG	671111	9.5	9.47	1	671221	24.0	680.0	66.0	6.0	3.6	0.0	6.8	60.0	524.6	190.0	750.1	3.5	1.8	2.0	2851	2029	31.35	31.78	-0.7	207
208	NSHORE 2	SPRG	671112	10.0	9.39	25	671221	24.0	78.0	9.2	1.7	0.5	0.0	0.3	48.0	85.4	5.7	10.0	0.2	0.0	0.0	365	227	3.73	3.55	2.4	208
209	NSHORE 5	SPRG	671112	22.0	9.52	60	671221	24.0	130.0	11.0	0.6	0.1	0.0	0.7	114.0	54.9	12.0	32.0	0.9	4.4	0.0	513	356	5.98	5.82	1.3	209
210	ANDYTHOM	SURF	671112	3.0	8.06	900	671221	16.0	3.2	1.3	6.4	1.0	0.0	0.0	0.0	36.6	3.0	2.0	0.0	0.0	0.0	43	49	0.58	0.73	-11.1	210
211	WILSNCRK	SURF	671112	6.5	7.40	2400	671221	16.0	6.4	2.4	20.0	1.0	0.1	0.0	0.0	51.2	1.5	9.0	0.1	0.0	-0.0	122	81	1.42	1.07	13.7	211
212	MILL CRK	SURF	671112	8.5	7.28	910	671221	12.0	2.8	1.0	10.0	1.2	0.1	0.0	0.0	29.3	2.5	8.0	0.1	0.0	-0.0	60	52	0.75	0.72	1.6	212
213	DECHAMBD	WELL	671112	65.5	7.10	60	671221	85.0	390.0	8.5	17.0	2.4	1.1	5.0	0.0	462.6	330.0	90.0	4.0	0.9	0.0	1835	1130	18.16	18.00	0.5	213
214	GUALTERS	WELL	671113	11.0	9.57	8	671221	60.0	160.0	15.0	2.0	0.2	0.0	0.6	45.6	224.5	20.0	16.0	4.0	3.5	5.0	711	486	7.44	7.31	0.9	214
215	HEMSPRG	SPRG	671113	31.0	6.56	4	671221	110.0	600.0	54.0	92.0	37.2	0.1	8.4	0.0	1501.6	196.0	91.0	[illegible]	4.4	0.0	2975	1930	35.13	32.09	4.5	215
216	SAMPG	SPRG	671113	12.6	9.70	0	671221	70.0	650.0	50.0	14.0	4.0	0.0	12.0	312.0	414.8	280.0	107.0	1.0	2.6	-0.0	2727	1789	32.85	28.98	3.1	216
217	GR TREE	WELL	671009	14.0	9.0	5	671221	56.0	26.0	3.1	74.0	9.6	0.0	0.2	0.0	195.2	5.0	120.0	1.7	3.5	0.0	443	393	5.59	5.33	-2.1	217
302	SESHORE 1	SPRG	680221	12.0	7.40	10	690309	79.0	19.0	2.7	20.8	11.0	0.0	0.3	0.0	158.6	3.6	1.0	0.2	0.9	0.0	277	216	2.84	2.75	1.7	302
303	WARMSPG4	SPRG	680221	31.4	6.95	20	690307	110.0	472.0	38.0	248.0	0.6	0.1	3.6	0.0	1756.8	100.0	2.0	1.3	5.7	0.0	3671	1934	34.67	34.07	0.9	303
304	TYLEE247	WELL	680221	13.2	9.55	0	690309	9.0	288.0	30.0	2.2	0.0	0.3	1.9	48.0	317.2	135.0	111.5	0.0	0.0	0.0	1447	781	13.40	12.94	1.8	304
305	COYOTE	SPRG	680222	8.4	7.10	3	690709	62.0	22.0	4.3	41.6	15.8	0.0	0.0	0.0	244.0	6.4	6.0	0.2	0.0	0.0	454	259	4.42	4.37	0.6	305
306	DOUGHRTY	SPRG	680222	7.0	7.50	1	690309	44.0	16.0	2.4	29.6	13.4	0.0	0.0	0.0	183.0	9.0	6.0	0.1	0.9	0.0	367	211	3.34	3.40	-0.9	306
307	WEURFHAM	SPRG	680222	17.3	7.10	1	690307	51.0	44.0	8.1	3.4	2.1	0.0	0.0	0.0	128.1	9.0	7.1	0.4	1.3	0.0	272	169	2.46	2.54	-1.6	307
308	BURKHAM	SPRG	680222	16.4	7.05	0	690307	51.0	41.0	9.1	4.0	1.7	0.0	0.5	0.0	126.1	9.4	7.0	0.2	0.9	0.0	272	186	2.36	2.51	-3.1	308
309	TYREETON	WELL	680222	16.9	7.20	0	690307	43.0	47.0	12.0	9.6	10.1	0.3	0.2	0.0	176.8	10.1	11.0	0.2	0.4	0.0	320	237	3.66	3.50	0.9	309
310	PROGHTBL	SPRG	680222	10.0	8.50	0	680309	11.0	750.0	64.0	12.0	5.3	0.0	12.0	120.6	1186.3	290.7	52.0	1.2	21.1	0.0	3791	1972	35.40	34.29	1.6	310
311	TVDEETAB	SPRG	680222	16.6	7.50	0	690307	34.0	34.0	3.8	40.8	9.6	0.0	0.0	0.0	225.7	13.0	16.0	0.1	0.0	0.0	471	256	4.40	4.28	1.4	311
312	MONOVISA	SPRG	680223	9.7	7.35	0	690307	19.0	6.0	1.6	18.4	1.0	0.0	0.0	0.0	73.2	2.4	9.0	0.1	0.4	0.0	154	93	1.30	1.47	-6.1	312
314	BE PT A	SPRG	680223	10.6	8.05	41	690309	18.0	13.0	2.0	21.6	3.0	0.0	0.2	0.0	79.3	2.4	12.0	0.1	0.4	0.0	224	109	1.77	1.63	4.2	314
315	KIRKWELL	WELL	680224	11.4	7.60	0	690309	26.0	25.0	3.6	22.2	6.0	0.3	0.0	0.0	122.0	7.5	20.0	0.5	7.9	0.0	272	178	2.77	2.70	-0.2	315
401	HV SUB 1	SPRG	680505	9.6	0.0	0	740515	1.0	27000.0	1549.0	0.0	47.0	0.0	0.2	12240.0	4080.0	10400.0	11400.0	44.0	1.3	0.0	0	70152	1217.76	1171.54	1.9	401
402	PA TF 5	SPRG	680505	10.9	8.49	3	610515	16.0	21.0	3.0	18.4	1.4	0.0	0.0	0.0	97.6	6.8	14.0	0.0	0.4	0.0	178	127	2.03	2.33	-0.7	402

TABLE 14 – Continued

						gpm							ppm															
NO.	SAMPLE SITE	SOURCE	SAMPLE DATE	TEMP	PH	DISCHARGE	ANALYSIS DATE	SIO2	NA	K	CA	MG	FE	B	CO3	HCO3	CL	SO4	F	NO3	H2S	SPEC COND	TDS	EPM CATION	EPM ANION	EPM % IMBALANCE	NO.
403	LATRANCH	WELL	680505	16.5	7.73	0	680516	41.0	9.4	2.9	12.8	1.4	0.0	0.0	0.0	54.9	4.8	9.0	0.2	0.4	0.0	117	108	1.24	1.24	0.0	403
404	LOWRYLND	WELL	680505	0.0	7.78	0	680515	22.0	6.0	1.2	11.2	1.9	0.0	0.0	0.0	42.7	2.4	9.0	0.1	0.0	0.0	99	74	1.01	0.96	2.5	404
405	BP TT 1	SPRG	680507	11.4	8.58	40	680515	17.0	24.0	3.1	17.6	1.6	0.0	0.0	0.0	97.6	3.6	17.0	0.1	0.0	0.0	178	131	2.08	2.06	0.5	405
406	BP TT 3	SPRG	680507	10.4	8.64	12	680516	17.0	15.0	5.3	22.4	2.4	0.0	0.0	0.0	97.6	3.6	12.0	0.0	0.4	0.0	173	126	2.10	1.96	3.6	406
407	BP TT 4	SPRG	680507	11.3	0.0	0	680515	0.8	20800.0	1063.0	0.0	37.9	0.0	0.0	10800.0	976.0	12240.0	8000.0	36.0	0.9	0.0	99139	52655	900.23	889.50	0.6	407
408	MV SUB 7	SPRG	680507	10.4	0.0	0	680516	1.1	27200.0	1430.0	0.0	48.0	0.0	0.0	14150.0	3172.0	16800.0	12000.0	44.0	1.3	0.0	0	73244	1223.73	1249.88	-1.1	408
409	MV SUB 4	SPRG	680507	0.0	0.0	0	680516	1.3	26700.0	1400.0	0.0	47.0	0.0	0.0	14400.0	2928.0	16800.0	12000.0	42.0	1.3	0.0	0	72831	1201.13	1253.77	-2.1	409
410	REEDFORD	WELL	680508	12.4	8.77	2	680516	53.0	110.0	14.0	11.6	4.1	0.0	0.0	0.0	256.2	22.0	50.0	0.2	0.0	0.1	637	390	6.06	5.87	1.6	410
411	MONUVISM	SPRG	680510	11.1	8.21	20	680516	25.0	9.2	1.3	16.0	2.9	0.0	0.0	0.0	67.1	4.8	6.0	0.0	0.4	0.1	152	100	1.47	1.41	2.1	411
501	SOLU TT	SPRG	680621	53.9	7.80	0	680923	106.0	520.0	44.0	8.0	6.2	0.0	0.0	28.8	580.7	504.0	12.0	0.0	0.0	0.0	2975	1594	24.66	27.20	-4.9	501
502	PAUHA 1	SPRG	680621	75.6	0.0	0	680923	31.0	8000.0	305.0	0.0	0.0	0.0	227.0	2270.4	1859.3	6210.0	4310.0	26.5	0.0	0.0	40423	22294	355.80	372.40	-2.3	502
503	GETTAULT	WELL	680627	16.0	7.94	2	680923	43.0	110.0	18.3	8.0	1.0	0.0	0.0	24.0	250.6	36.4	27.0	0.0	0.0	0.0	570	394	5.73	6.63	-7.3	503
504	THOMAULT	WELL	680628	14.2	9.43	18	680920	27.0	126.0	19.6	4.8	1.0	0.0	0.0	44.9	128.3	28.0	52.0	0.0	0.0	0.0	626	466	6.30	6.30	-0.0	504
505	ANHANIAS	WELL	680628	16.4	0.0	1	680920	44.0	110.0	17.6	4.8	0.5	0.0	0.0	14.4	253.6	25.0	43.0	0.0	0.0	0.0	545	386	5.51	6.32	-6.8	505
506	PAUHA 3	SPRG	680802	7.8	9.80	10	680923	1.0	24200.0	1240.0	0.0	2.2	0.0	204.7	11520.0	5124.0	15300.0	11520.0	38.9	0.0	5.0	123978	66545	1084.60	1141.30	-2.5	506
507	PAUHA 1	SPRG	680802	70.3	8.96	20	680923	31.0	7850.0	330.0	0.0	0.0	0.0	102.3	2424.0	3025.6	6270.0	4000.0	28.5	0.0	5.0	30131	22583	349.92	393.22	-5.8	507
508	PAUHA 5	SPRG	680802	21.6	6.78	30	680923	71.0	100.0	20.4	63.2	37.4	0.0	0.0	0.0	667.6	32.2	11.0	0.0	0.0	0.0	1331	633	11.10	11.09	0.0	508
509	RANCHERA	SPRG	680731	13.3	7.41	1	680923	48.0	8.2	4.2	11.2	2.4	0.0	0.0	0.0	44.5	10.0	10.0	0.0	0.0	0.0	173	115	1.22	1.22	0.0	509
510	MURPHY	SPRG	680814	13.6	8.40	10	680923	42.0	9.8	2.2	4.0	4.8	0.0	0.0	4.8	39.0	8.0	9.0	0.0	0.0	0.0	117	103	1.08	1.21	-5.9	510
511	GRYCREEK	SPRG	680805	8.6	7.11	5	680923	49.0	5.4	3.1	1.6	1.0	0.0	0.0	0.0	8.5	6.0	7.0	0.0	0.0	0.0	37	77	0.47	0.47	0.1	511
512	HWL 2	WELL	680818	15.7	9.82	0	680923	10.2	3940.0	268.0	0.5	2.4	0.0	102.3	1668.0	1506.6	2380.0	2430.0	10.6	0.0	0.0	18539	11555	178.48	198.77	-5.4	512
513	HWL10	WELL	680814	11.4	9.09	0	680923	34.0	780.0	48.0	2.4	0.5	0.0	0.0	177.6	829.6	417.0	200.0	0.0	0.0	0.1	0	2057	35.32	35.16	0.2	513
514	HWL 1	WELL	680814	22.6	8.73	0	680923	30.0	438.0	37.6	2.4	1.4	0.0	0.0	72.0	658.8	180.0	155.0	0.0	0.0	0.0	1859	1254	20.25	21.67	-3.4	514
515	TYREE ZIP	WELL	680819	13.3	9.41	0	680923	34.0	268.0	26.7	0.8	0.1	0.0	0.0	14.4	258.0	140.0	135.0	0.0	0.0	0.0	1239	746	12.39	11.48	3.8	515
516	TYREE TOC	WELL	680819	17.6	7.51	0	680920	55.0	42.4	11.6	6.4	3.8	0.0	0.0	0.0	136.6	22.0	19.0	0.0	0.0	0.0	347	227	2.78	3.26	-7.9	516
517	MVSUB 6	SPRG	680830	13.9	0.0	0	680923	1.6	26800.0	1450.0	0.0	94.6	0.0	269.3	14440.0	4819.0	17000.0	15400.0	43.9	0.0	0.0	123978	78487	1210.67	1380.19	-6.5	517
518	WAFORD	SPRG	690601	11.8	8.20	0	690612	51.0	29.0	11.0	25.6	4.8	0.0	0.0	0.0	180.6	10.0	10.0	0.0	0.0	0.0	322	238	3.22	3.62	-5.9	518
601	PAUHA	WELL	690524	18.6	7.50	0	690612	114.0	300.0	50.0	28.8	9.6	0.0	0.0	0.0	766.2	156.0	10.0	0.0	0.0	0.0	1497	1045	16.56	17.16	-1.8	601
602	KELLY'S	WELL	690526	11.6	7.21	0	690612	28.0	45.0	12.3	97.6	4.8	0.0	0.0	0.0	361.1	34.0	61.0	0.0	0.0	0.0	743	479	7.53	8.56	-6.4	602
603	HIGHWAY4	WELL	690528	15.5	8.48	0	690612	59.0	56.0	11.0	12.8	6.7	0.0	0.0	0.0	175.7	14.0	29.0	0.0	0.0	0.0	334	274	3.91	3.88	0.4	603
604	CHASEROH	WELL	690528	15.0	7.01	0	690612	75.6	33.0	8.0	17.6	12.5	0.0	0.0	0.0	205.0	10.0	9.0	0.0	0.0	0.0	433	265	3.54	3.83	-3.9	604

LABORATORY ANALYSES OF WATER SAMPLES FROM
MONO LAKE, CALIFORNIA

TABLE 14 — Continued

SAMPLES 201 THROUGH 604

SMPL NO.	CATIONS %NA	CATIONS % K	CATIONS %CA	CATIONS %MG	ANIONS %CO3	ANIONS HCO3	ANIONS %CL	ANIONS %SO4	ANIONS % F	ANIONS %NO3	ANIONS %OH	NA /K	NA /CL	K /CL	B/CL (PPM)	SO4 /CL	NA/ SIO3	K/ SIO3	CA/ SIO3	MG/ SIO3	% SIO2 (PPM)	COND. FACTOR	CA /MG	NA+K /SIO3	CA+MG /SIO3
201	77.7	3.0	14.3	5.0	0.0	76.8	15.6	7.3	0.3	0.0	0.0	25.9	5.7	0.22	0.0	0.47	9.9	0.38	1.8	0.6	4.4	0.644	2.83	10.32	2.47
202	97.2	2.5	0.0	0.3	36.5	7.4	37.5	18.5	0.2	0.0	0.0	38.9	2.5	0.07	0.027	0.49	******	381.01	0.0	45.0	0.0	0.612	0.0	*******	45.35
203	62.6	3.1	25.4	8.9	0.0	89.4	7.1	3.0	0.2	0.4	0.0	20.2	9.3	0.46	0.049	0.42	6.9	0.34	2.8	1.0	5.1	0.671	2.84	7.21	3.76
204	13.0	4.3	49.8	32.9	0.0	83.7	4.7	11.6	0.0	0.0	0.0	3.1	2.3	0.76	0.0	2.46	0.2	0.08	0.9	0.6	22.5	0.942	1.52	0.31	1.49
205	27.2	6.4	66.5	0.0	0.0	77.5	9.1	13.4	0.0	0.0	0.0	4.3	4.6	1.09	0.0	1.48	0.4	0.08	0.9	0.0	34.6	0.693	999.99	0.44	0.07
206	91.1	2.4	3.9	2.6	28.6	50.0	7.0	14.1	0.0	0.3	0.0	37.5	14.3	0.38	0.043	2.03	3.1	0.08	0.1	0.1	14.2	0.625	1.52	3.18	0.22
207	94.3	3.8	1.0	0.9	6.3	27.1	16.9	49.1	0.6	0.1	0.0	25.1	5.5	0.22	0.036	2.91	37.0	1.47	0.4	0.4	1.2	0.712	1.01	38.48	0.75
208	91.0	6.3	1.6	1.1	45.1	39.4	4.7	10.6	0.3	0.0	0.0	14.4	20.4	1.41	0.051	2.25	4.2	0.29	0.1	0.0	10.6	0.621	1.52	4.54	0.12
209	94.6	4.7	0.5	0.1	65.3	15.5	5.8	11.4	0.8	1.2	0.0	20.1	16.7	0.83	0.017	1.97	7.1	0.35	0.0	0.0	6.7	0.580	4.05	7.43	0.05
210	24.0	7.5	55.0	13.6	0.0	82.6	11.7	5.7	0.0	0.0	0.0	3.2	1.6	0.51	0.0	0.49	0.3	0.09	0.7	0.2	28.4	1.135	4.05	0.39	0.85
211	19.7	4.3	70.4	5.6	0.0	78.1	3.9	17.4	0.5	0.0	0.0	4.5	6.6	1.45	0.0	4.43	0.5	0.12	1.9	0.1	19.6	0.665	12.64	0.64	2.02
212	16.3	3.4	67.0	13.2	0.0	66.4	9.8	23.1	0.7	0.0	0.0	4.8	1.7	0.36	0.0	2.36	0.3	0.06	1.2	0.2	23.0	0.857	5.06	0.37	1.50
213	93.3	1.2	4.4	1.1	0.0	36.7	51.7	10.4	1.2	0.1	0.0	78.0	1.8	0.02	0.018	0.20	6.0	0.08	0.3	0.1	7.5	0.616	4.05	6.07	0.35
214	93.6	4.8	1.3	0.3	20.8	50.3	7.7	19.9	0.4	0.8	0.0	19.4	12.3	0.63	0.030	2.58	3.5	0.18	0.0	0.0	12.3	0.666	5.06	3.66	0.06
215	74.3	3.9	13.1	8.7	0.0	76.6	17.2	5.9	0.0	0.2	0.0	18.9	4.7	0.25	0.043	0.34	7.1	0.38	1.3	0.8	5.7	0.649	1.50	7.50	2.09
216	91.6	4.8	2.3	1.3	35.9	23.5	27.2	12.9	0.3	0.1	0.0	19.1	3.6	0.19	0.043	0.47	12.1	0.64	0.3	0.2	3.9	0.656	1.77	12.77	0.47
217	19.9	1.4	64.9	13.9	0.0	53.9	2.4	42.1	0.6	1.0	0.0	14.3	8.0	0.56	0.0	17.72	0.6	0.04	2.0	0.4	14.2	0.815	4.68	0.65	2.40
302	29.1	2.4	36.5	32.0	0.0	94.6	3.7	0.8	0.4	0.5	0.0	12.0	8.1	0.68	0.0	0.21	0.3	0.03	0.4	0.3	36.5	0.726	1.14	0.34	0.74
303	59.2	2.8	35.7	2.3	0.0	84.5	14.9	0.1	0.2	0.3	0.0	21.1	4.0	0.19	0.020	0.01	5.6	0.27	3.4	0.2	5.7	0.557	15.67	5.87	3.59
304	93.5	5.7	0.8	0.0	12.4	40.2	29.4	17.7	0.3	0.0	0.0	16.3	3.3	0.20	0.013	0.60	41.8	2.56	0.4	0.0	1.2	0.525	999.99	44.36	0.36
305	21.7	1.9	47.0	29.5	0.0	91.5	5.4	2.9	0.2	0.0	0.0	11.3	4.0	0.36	0.0	0.53	0.7	0.06	1.5	0.9	16.2	0.558	1.59	0.74	2.42
306	20.8	1.8	44.2	33.1	0.0	88.3	7.5	3.7	0.2	0.4	0.0	11.3	2.7	0.24	0.0	0.49	0.5	0.04	1.0	0.8	20.8	0.609	1.34	0.52	1.76
307	77.7	8.4	7.0	6.9	0.0	82.6	10.0	5.7	0.8	0.8	0.0	9.2	7.5	0.82	0.0	0.57	1.1	0.12	0.1	0.1	26.9	0.694	1.01	1.25	0.20
308	75.6	9.9	8.5	6.0	0.0	83.8	9.4	5.8	0.4	0.6	0.0	7.7	7.5	0.98	0.048	0.62	1.1	0.14	0.1	0.1	27.3	0.684	1.40	1.19	0.20
309	55.9	8.4	13.1	22.7	0.0	77.9	14.1	7.5	0.3	0.2	0.0	6.7	4.0	0.60	0.011	0.53	1.4	0.21	0.3	0.6	18.1	0.609	0.58	1.64	0.91
310	92.4	4.6	1.7	1.2	12.6	56.8	23.8	5.6	0.2	1.0	0.0	19.9	4.0	0.20	0.041	0.23	89.1	4.47	1.6	1.2	0.6	0.522	1.38	93.54	2.82
311	33.6	2.2	46.3	17.9	0.0	86.4	8.6	4.9	0.1	0.0	0.0	15.2	4.0	0.27	0.0	0.57	1.3	0.09	1.8	0.7	13.3	0.544	2.58	1.39	2.50
312	20.1	3.2	70.7	6.1	0.0	81.8	4.6	12.8	0.4	0.5	0.0	6.4	3.9	0.60	0.0	2.77	0.4	0.06	1.5	0.1	20.2	0.606	11.63	0.48	1.58
314	31.9	2.9	60.8	4.5	0.0	79.8	4.2	15.3	0.3	0.4	0.0	11.1	8.4	0.76	0.0	3.69	0.9	0.09	1.8	0.1	16.4	0.535	13.65	1.03	1.93
315	39.2	3.3	39.6	17.8	0.0	71.9	7.6	15.0	0.9	4.6	0.0	11.8	5.1	0.44	0.0	1.97	1.3	0.11	1.3	0.6	14.5	0.655	2.22	1.36	1.84
401	96.4	3.2	0.0	0.3	34.8	6.8	39.7	18.5	0.2	0.0	0.0	29.8	2.5	0.08	0.0	0.47	******	*******	0.0	116.2	0.0	******	0.0	*******	116.17
402	45.1	3.8	45.3	5.8	0.0	78.7	6.7	14.3	0.0	0.3	0.0	11.9	6.7	0.57	0.0	2.15	1.7	0.14	1.7	0.2	12.6	0.640	7.75	1.86	1.95

TABLE 14 – Continued

SMPL	CATIONS				ANIONS																				
NO.	%NA	% K	%CA	%MG	%CO3	HCO3	%CL	%SO4	% F	%NO3	%OH	NA /K	NA /CL	K /CL	B/CL (PPM)	SO4 /CL	NA/ SIO3	K/ SIO3	CA/ SIO3	MG/ SIO3	% SIO2 (PPM)	COND. FACTOR	CA /MG	NA+K /SIO3	CA+MG /SIO3
403	33.0	6.0	51.5	9.5	0.0	72.6	10.9	15.1	0.8	0.6	0.0	5.5	3.0	0.55	0.0	1.38	0.3	0.05	0.5	0.1	37.6	0.925	5.39	0.35	0.55
404	25.9	3.0	55.4	15.7	0.0	72.9	7.0	19.5	0.5	0.0	0.0	8.5	3.9	0.45	0.0	2.77	0.4	0.04	0.8	0.2	29.4	0.754	3.54	0.40	0.98
405	50.2	3.8	42.2	3.8	0.0	77.6	4.9	17.2	0.3	0.0	0.0	13.2	10.3	0.78	0.0	3.49	1.8	0.14	1.6	0.1	12.9	0.662	11.12	1.98	1.69
406	31.0	6.4	53.1	9.4	0.0	81.7	5.2	12.8	0.0	0.4	0.0	4.8	6.4	1.34	0.0	2.46	1.2	0.24	2.0	0.3	13.5	0.727	5.66	1.39	2.32
407	96.6	3.0	0.0	0.3	40.5	1.8	38.8	18.7	0.2	0.0	0.0	32.1	2.5	0.08	0.0	0.48	************		0.0	117.1	0.0	0.531	0.0	*******	117.06
408	96.7	3.0	0.0	0.3	37.8	4.2	37.9	20.0	0.2	0.0	0.0	32.3	2.5	0.08	0.0	0.53	******	998.62	0.0	107.8	0.0	******	0.0	*******	107.77
409	96.7	3.0	0.0	0.3	38.3	3.8	37.8	19.9	0.2	0.0	0.0	32.4	2.5	0.08	0.0	0.53	******	827.26	0.0	89.4	0.0	******	0.0	*******	89.36
410	79.0	5.9	9.6	5.5	0.0	71.5	10.6	17.7	0.2	0.0	0.0	13.4	7.7	0.58	0.0	1.68	2.7	0.20	0.3	0.2	13.6	0.643	1.73	2.91	0.52
411	27.2	2.3	54.4	16.1	0.0	78.1	9.6	11.8	0.0	0.5	0.0	12.0	3.0	0.25	0.0	1.23	0.5	0.04	1.0	0.3	24.8	0.706	3.37	0.52	1.24
$\boxed{501}$	91.7	4.6	1.6	2.1	3.5	35.0	$\underline{60.6}$	0.9	0.0	0.0	0.0	20.1	1.4	0.07	0.0	0.02	6.4	0.32	0.1	0.1	6.6	0.536	0.78	6.73	0.26
$\boxed{502}$	97.8	2.2	0.0	0.0	20.3	8.2	$\underline{47.0}$	24.1	0.4	0.0	0.0	44.6	2.0	0.04	0.037	0.51	337.1	7.56	0.0	0.0	0.1	0.552	0.0	344.67	0.0
503	83.5	8.2	7.0	1.4	12.1	64.0	15.5	8.5	0.0	0.0	0.0	10.2	4.7	0.46	0.0	0.55	3.3	0.33	0.3	0.1	10.9	0.692	5.06	3.67	0.33
504	87.0	8.0	3.8	1.3	23.7	33.4	12.5	30.4	0.0	0.0	0.0	10.9	6.9	0.63	0.0	2.43	6.1	0.56	0.3	0.1	6.6	0.649	3.03	6.65	0.35
505	86.8	8.2	4.3	0.7	7.6	67.1	11.2	14.2	0.0	0.0	0.0	10.6	6.8	0.64	0.0	1.27	3.3	0.31	0.2	0.0	11.4	0.708	6.07	3.57	0.19
506	97.1	2.9	0.0	0.0	33.6	7.4	37.8	21.0	0.2	0.0	0.0	33.2	2.4	0.07	0.013	0.56	******	952.53	0.0	5.3	0.0	0.537	0.0	*******	5.33
$\boxed{507}$	97.6	2.4	0.0	0.0	20.5	12.6	$\underline{45.0}$	21.5	0.4	0.0	0.0	40.5	1.9	0.05	0.016	0.48	330.8	8.18	0.0	0.0	0.1	0.749	0.0	338.97	0.0
$\boxed{508}$	39.2	4.7	28.4	27.7	0.0	89.8	8.2	2.1	0.0	0.0	0.0	8.3	4.8	0.57	0.0	0.25	1.8	0.22	1.3	1.3	11.2	0.487	1.02	2.06	2.64
509	29.2	8.8	45.8	16.2	0.0	59.8	23.1	17.1	0.0	0.0	0.0	3.3	1.3	0.38	0.0	0.74	0.2	0.07	0.3	0.1	41.4	0.668	2.83	0.29	0.47
510	39.6	5.2	18.5	36.7	13.2	52.8	18.6	15.4	0.0	0.0	0.0	7.6	1.9	0.25	0.0	0.83	0.3	0.04	0.1	0.3	40.5	0.881	0.51	0.35	0.42
511	49.7	16.8	16.9	16.7	0.0	29.7	39.4	30.9	0.0	0.0	0.0	3.0	1.3	0.43	0.0	0.78	0.1	0.05	0.0	0.0	62.9	2.093	1.01	0.19	0.10
512	96.0	3.8	0.0	0.1	28.0	12.4	33.8	25.5	0.4	0.0	0.0	25.0	2.6	0.10	0.043	0.75	504.6	20.18	0.1	0.6	0.1	0.621	0.11	524.78	0.70
513	96.1	3.5	0.3	0.1	16.8	38.7	32.6	11.8	0.0	0.0	0.0	27.6	3.0	0.11	0.0	0.36	30.0	1.08	0.1	0.0	1.7	******	3.03	31.05	0.14
$\boxed{514}$	94.1	4.7	0.6	0.6	11.1	49.8	24.2	14.9	0.0	0.0	0.0	19.8	3.6	0.18	0.0	0.62	15.1	0.76	0.1	0.1	3.0	0.674	1.01	15.82	0.19
515	94.1	5.5	0.3	0.1	4.2	36.9	34.4	24.5	0.0	0.0	0.0	17.1	3.0	0.17	0.0	0.71	10.3	0.60	0.0	0.0	4.6	0.602	5.06	10.90	0.04
516	66.4	10.7	11.5	11.4	0.0	68.8	19.1	12.2	0.0	0.0	0.0	6.2	3.0	0.48	0.0	0.64	1.0	0.16	0.2	0.2	24.2	0.655	1.01	1.17	0.35
517	96.3	3.1	0.0	0.6	34.9	5.7	36.0	23.2	0.2	0.0	0.0	31.4	2.3	0.07	0.015	0.65	************		0.0	233.5	0.0	0.633	0.0	*******	233.53
518	39.2	8.8	39.7	12.3	0.0	81.8	7.8	10.4	0.0	0.0	0.0	4.5	4.5	1.00	0.0	1.33	0.7	0.17	0.8	0.2	21.4	0.739	3.24	0.91	0.98
$\boxed{601}$	78.8	7.7	8.7	4.8	0.0	73.2	25.6	1.2	0.0	0.0	0.0	10.2	3.0	0.29	0.0	0.05	3.4	0.34	0.4	0.2	10.9	0.702	1.82	3.77	0.59
602	26.0	4.1	64.7	5.2	0.0	69.1	11.2	19.7	0.0	0.0	0.0	6.4	2.0	0.32	0.0	1.76	2.1	0.33	5.2	0.4	5.8	0.645	12.34	2.43	5.65
603	62.3	7.2	16.3	14.1	0.0	74.2	10.2	15.6	0.0	0.0	0.0	8.7	6.2	0.71	0.0	1.53	1.2	0.14	0.3	0.3	21.5	0.715	1.16	1.38	0.61
604	40.5	5.8	24.8	29.0	0.0	87.7	7.4	4.9	0.0	0.0	0.0	7.0	5.1	0.73	0.0	0.66	0.6	0.08	0.4	0.4	28.2	0.613	0.86	0.66	0.76

TABLE 15·COPY OF LOG OF WELL DRILLED ON PAOHA ISLAND, MONO LAKE, MONO COUNTY, CALIFORNIA, DURING 1908*

First 1005 feet were shale:
Strong seepage of oil between 350 and 460 feet
Strong seepage of oil between 725 and 730 feet
At 1000 ft water was standing within 30 to 40 ft of top, this being lake water (alkali).
Past 1000 ft water changed from alkali to fresh

1005–1065 ft	water, sand
1065–1075 ft	shale
1075–1090 ft	water, sand
1090–1110 ft	sand and shale in alternate layers
1110–1140 ft	gray shale
1140–1175 ft	black shale
1175–1190 ft	water, sand
1190–1245 ft	black shale, sandy
1245–1260 ft	gray shale, sandy
1260–1350 ft	dark and tough shale
1350–1400 ft	light-pink rock, very hard
1400–1480 ft	light-pink sand
1480–1625 ft	dark-red sand
1625–1705 ft	dark shale
1705–1730 ft	sand, more water and water quite warm
1730–1792 ft	dark shale
1792–1810 ft	sand—more water
1810–1900 ft	dark shale
1900–1998 ft	light shale

"Strongest seepage of oil between 1200 and 1350 ft, all the way."
"This probably would have produced a paying well if water had been shut off."

---

[*] This log is reproduced as originally recorded by R. W. Pack, U. S. Geological Survey. Comments regarding oil-shows are evidently those of the driller or well promoter; they are doubted by us but are included for completeness and for historical interest. Well log was furnished by Dr. G. I. Smith, U. S. Geological Survey, Menlo Park, California.

Table after Scholl and others (1967).

recorded. In 1969, the well flowed at 240 liters/min at 65.5°C from a discharge pipe approximately 400 meters from the well head. In October, 1978 for this study, a temperature of 67°C was measured at the standpipe above the well head and a temperature of 66°C was measured at the discharge pipe. Mariner and others (1977) determined that the deuterium composition of the water from this well is similar to that of fresh water in the basin, thus they concluded that the water is meteoric and is not a mixed water (combination of water from a deep origin and meteoric water. A schematic cross section by Lee (1969) through this well and the well on Paoha Island is shown in Figure 14.

Lee (1969) determined approximate geothermal gradients for six wells, listed below and shown on Plate 2, by either direct temperature-depth recordings or by subtracting the mean annual surface temperature from the temperature of the well water and then dividing by the speculated depth of the source of the water:

Well	Gradient
Cain Ranch	1°C/11.8 meters
Tyree 217	1°C/15.6 m
Tyree Too	1°C/10.2 m
Great Western	1°C/14.1 m
Highway 3	1°C/15.2 m
Dechambeau	1°C/ 5.4 m

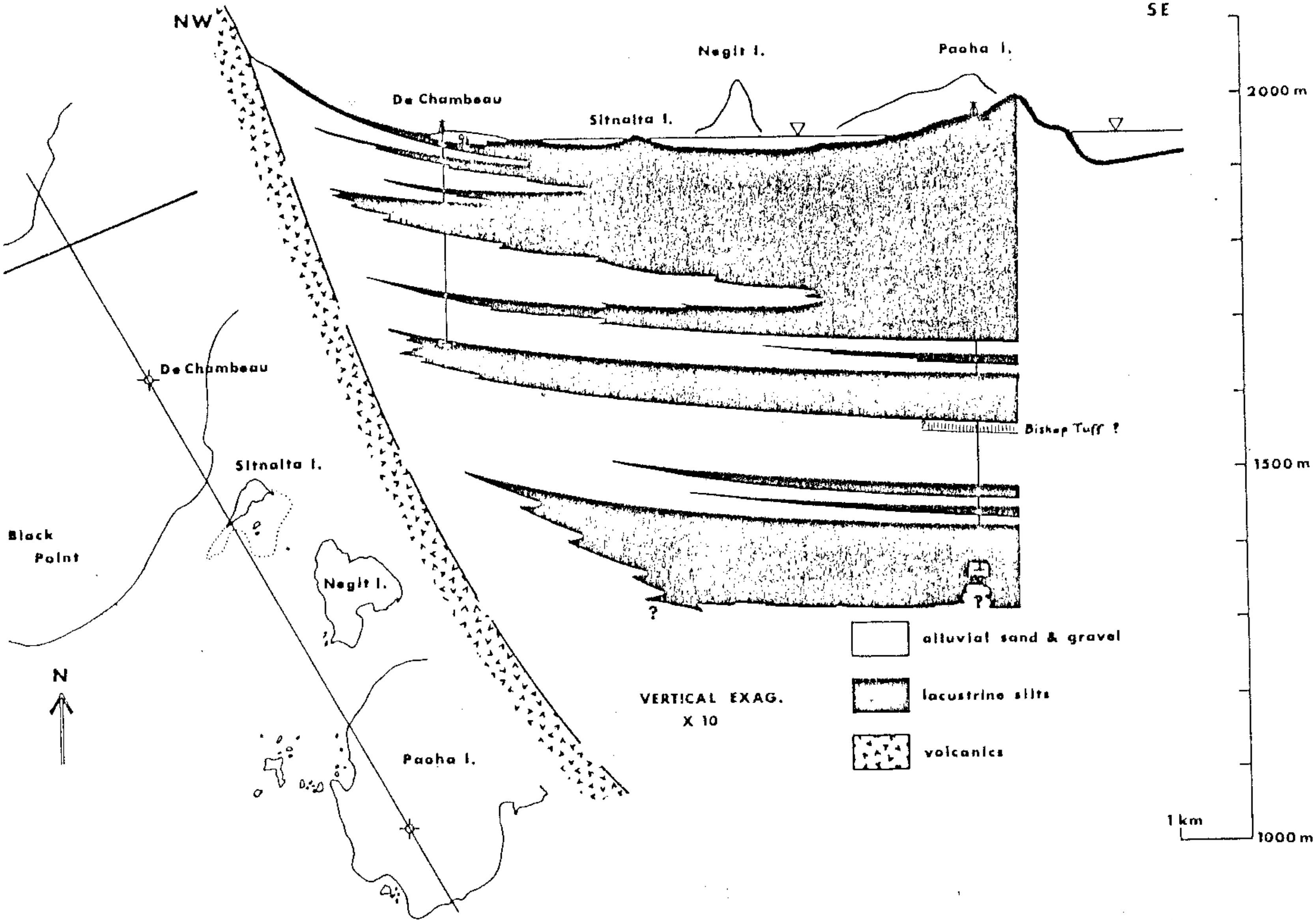


Figure 14 — Cross-section, Black Point-Paoha Island. After Lee (1969).

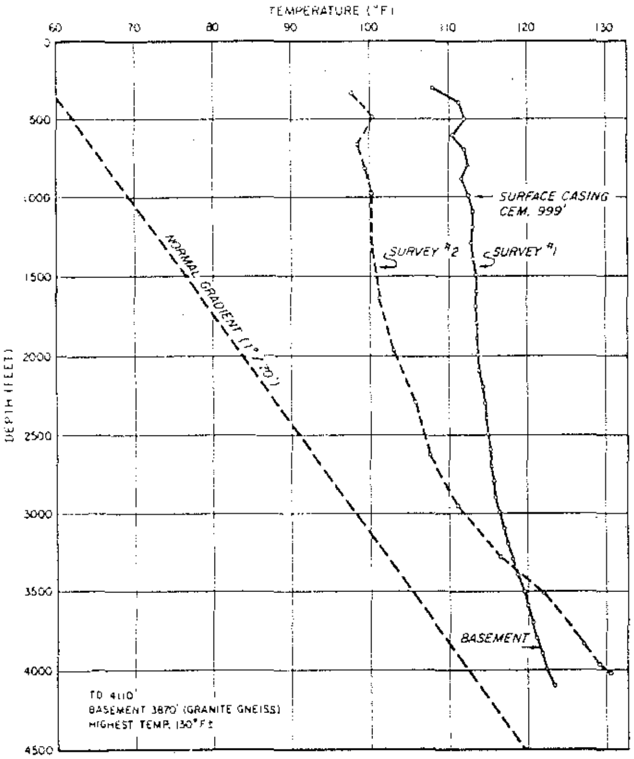
Exploratory Geothermal Wells

During the fall of 1971, two exploratory geothermal wells were drilled on the shores of Mono Lake (Plate 2). Neither encountered a high temperature or a high geothermal gradient, therefore, both were abandoned. Figures 15 and 16 present generalized lithologic columns and geothermal gradients of the two wells. In 1974, the U.S. Geological Survey redrilled the holes and ran more geothermal gradient tests only to find that the gradients were "normal" for the Sierra Nevada-Basin and Range transition zone (written communication to California Division of Oil and Gas).

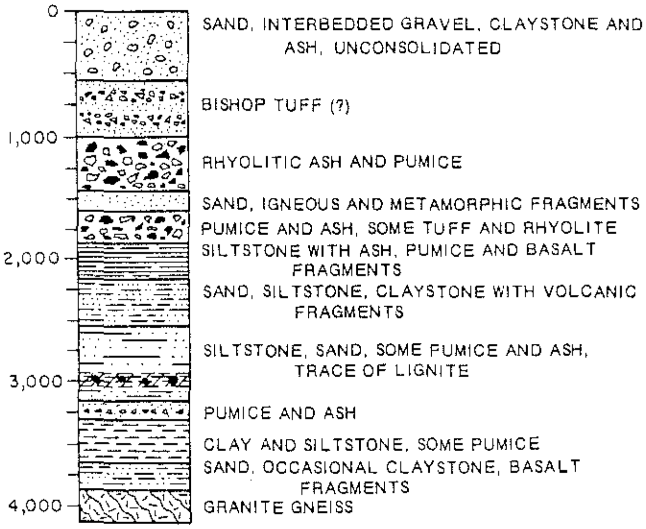
In regard to the structural configuration of the basin, lithologic data from both wells support the hypothesis of Gilbert and others (1968) rather than the hypothesis of Pakiser and others (1960). Gneissic granite basement was reached at only 1,180 meters in the well (PRC 4397.1) on the south shore, which had a maximum recorded temperature of approximately 54°C at about 1,220 meters. The well (PRC 4572.1) on the northwest shore reached basement (granodiorite) at only 532 meters and had a maximum temperature of about 57°C at a total depth of 743 meters. The relatively low temperatures of the two wells indicate the vagaries of the geothermal reservoir, especially since surface evidence (Holocene volcanic rocks, thermal springs, thermal wells, etc.) of geothermal heat is close to the drilling sites.

SOURCE OF GEOTHERMAL HEAT

It appears that there are two major processes responsible for the geothermal anomalies in Mono Basin. These are 1) deep circulation

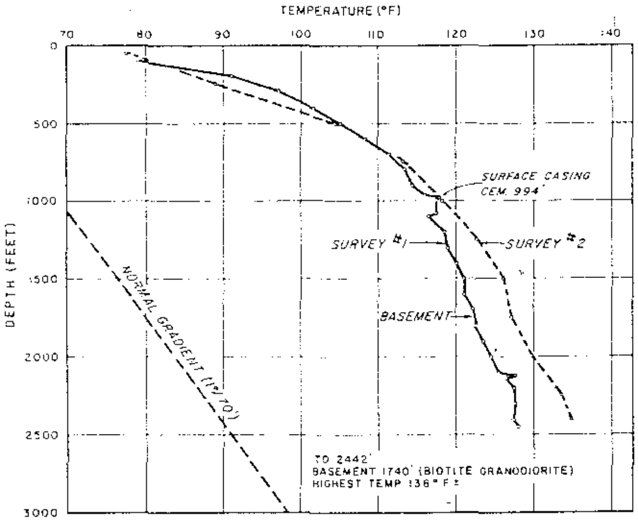


Temperature surveys of the Mono Lake exploratory geothermal well "State PRC 4397.1" 1 drilled by Geothermal Resources International, Inc. *Data courtesy GRI, Inc.*

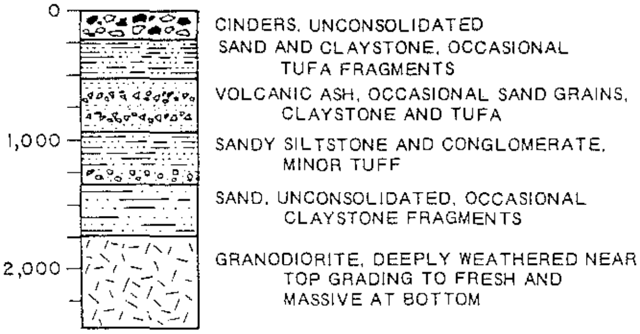


Lithologic column of the Mono Lake exploratory well "State PRC 4397.1" 1.

FIGURE 15 – Survey and column after Axtell (1972).



Temperature surveys of the Mono Lake exploratory geothermal well "State PRC 4572.1" 23-1 drilled by Getty Oil Co. *Data courtesy Getty Oil Co.*



Lithologic column of the Mono Lake exploratory well "State PRC 4572.1" 23-1.

FIGURE 16 – Survey and column after Axtell (1972).

of ground water along faults and 2) a body of magma that underlies part of the basin. Of these processes, the second is more speculative because of the lack of direct evidence of a magma chamber.

The thermal springs along the west shore and east shore of Mono Lake are noticeably less warm than those in the central and southern parts of the lake area. Both sets coincide with large northwest-trending faults that probably allow descending ground water to become heated by the geothermal gradient and then rise to the surface as springs.

Bailey and others (1976) feel that a magma chamber may underlie the area encompassed by Kistler's ring-fracture zone and that this chamber may be rising and thus be capable of feeding further eruptions. They cite the recency and frequency of eruptions at Mono Craters as evidence for this chamber.

The swarms of earthquakes reported by Ryall and Ryall (1979) raise speculation as to whether or not a magma chamber underlies the east part of Mono Basin. The coincidence of the swarms with the same time period each year, however, suggests other causes of the seismicity.

Of greatest interest is the cause of the thermal anomalies under the central and northern parts of Mono Lake. The following evidence suggests that there is still communication between this surface area and molten material: 1) fumaroles and near-boiling thermal springs on Paoha Island, 2) the very young volcanic rocks on Paoha and Negit Islands and at Black Point, 3) the chloride-rich thermal waters from Dechambeau well, from the hot spring in the northern part of the lake and from the hot springs on Paoha Island, and 4) the high lithium content of the springs on Paoha Island and along the south shore of the lake. A large gravity low underlies this area (Pakiser and others, 1960), but this low could be explained just as well by very low density sediments as by a magma chamber. Consideration of all data, including the observation that the exploratory geothermal well on the north shore of the lake appears to be hotter than the one on the south shore, suggests that the area that includes Dechambeau well, the hot spring in the lake, and Paoha Island is the hottest in the basin.

LOCAL CULTURAL, ECONOMIC, AND ENVIRONMENTAL CONDITIONS

Mono Basin is sparsely settled and, according to Hannah (1975), had only about 700 people as of the middle 1970's. Most of these people live in the community of Lee Vining (Plate 2), which is on the west shore of Mono Lake. Except for a few residences and ranch houses in the north part of the basin, most of the cultural development is in Lee Vining or very near it along U.S. Highway 395.

Nearly 83% of the land in the basin is controlled by the Federal Government or owned by the City of Los Angeles (California Department of Water Resources, 1964). Because the property owned by the City is watershed, the Federal Government in 1931 withdrew much of the public land from entry in order to protect the City's water supply. This withdrawal, although it permits livestock grazing, mining, and recreation, forbids homesteading and farming. Consequently, population growth and development of water supplies in the basin have been restricted.

The road system in the basin is very limited. The only major paved roads are State Highways 167 and 120 and U.S. Highway 395.

The latter is a major service artery along the east side of the Sierra Nevada and is kept open all year. There are many graded and dirt roads, but most are passable only to four-wheel drive vehicles because of the soft pumice sands. Because of the high elevation of the basin, ice and snow are a problem during the winter months.

The economy of the basin depends mostly upon the service and tourist industry. Essentially all of the former and much of the latter are confined to the west side of Mono Lake in the vicinity of Lee Vining. There is some cattle ranching, and a small company harvests brine shrimp from Mono Lake.

Mono Basin and especially Mono Lake are the subject of much environmental concern mainly because they serve as important wildlife sanctuaries and outdoor recreation areas. Some of the areas of most promise as sources of geothermal heat (for example, Paoha Island) are also areas that some people want to keep in their natural state.

CONCLUSIONS AND RECOMMENDATIONS

The greatest amount of geothermal activity in Mono Basin appears to be within a north-northwest-trending thermal zone that includes the Dechambeau well, the thermal spring in northern Mono Lake, Paoha Island, and thermal springs on the south shore of the lake (Plate 2). Some of the thermal water is from deep aquifers, but some water may also ascend directly from a magma chamber along faults and then become mixed with meteroric or lake water. Cold springs on Paoha Island and the relatively low temperatures in the two exploratory geothermal holes indicate, however, that the zone cannot be construed as a simple, continuous reservoir of thermal water.

Areas of less geothermal activity include springs along the west, northwest, and east shore areas of Mono Lake. The first two areas are not very favorable because of their low heat, while the springs on the east shore have only moderate temperature and have poor accessibility

Because of both the limited cultural and economic development in the basin and a local desire to keep development limited, space heating and ice and snow control on roads are probably the most attractive uses of the geothermal heat. If the resources of the linear thermal zone were used, however, they would have to be piped several kilometers. For example, the distance from the springs on the south shore of Mono Lake to Lee Vining is about 8 km. The average distance from the Dechambeau well (whose thermal water is currently draining unused into a pond) to a number of structures along U.S. Highway 395 is about 6 - 7 km. Nevertheless, John Lund of the Oregon Institute of Technology has reported to the California Department of Transportation that the temperature loss in Iceland is only about 0.69°C/km and that thermal water is commonly transported 11 and 12 km. Paoha Island presents an additional problem, however, in that it is nearly surrounded by deep water and is a sanctuary for wildlife.

Future geological studies should emphasize exploration in the area between Highway 395 and the linear thermal zone discussed above. This exploration could include shallow temperature-probe holes on a grid pattern and heat flow measurements in possibly two bore holes of moderate depth, one between Black Point and Highway 395 and one in the vicinity of Rush Creek, southeast of Lee Vining. Such a study might reveal thermal waters of adequate temperature and quantity that could be used in Lee Vining or in the scattered buildings and residences to the north.

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LOW-TEMPERATURE GEOTHERMAL RESOURCES OF THE SOUTH BAY AREA OF SAN DIEGO COUNTY

INTRODUCTION

The south San Diego Bay area of San Diego County, situated in the very southwest corner of California, was studied in reconnaissance fashion for its low-temperature geothermal resources. The area of detailed study included four townships and is shown in Figure 17. Downtown San Diego is about 15 km northwest of the study area.

Cultural development is extensive in the Imperial Beach-Chula Vista area, but is much less so in the Tia Juana River valley, and even less on Otay Mesa. The climate is mild as mean annual temperatures are in the high teens in degrees Celsius. Precipitation is about 254-330 millimeters and falls mostly during the winter months in the form of rain (CDWR Bulletin 106-2, 1967). Geographically, the study area is part of a coastal plain, which is characterized by a series of dissected, wave-cut terraces of different levels that extend inland from the coast for approximately 15 km.

The only available report that discusses geothermal phenomena in the area is that by Wiegand (1970). He discussed data presented in CDWR Bulletin 106-2, which were used as evidence for a fault zone through San Diego Bay and Tijuana, Mexico. Discussions with several individuals (Jerry Pinckney, Robert McKuen, Kathe Bertine, Mike Kennedy, Don Lande, Keith Johnson) indicates that no detailed study or exploration of the geothermal resources of this area have been undertaken. Information in this report was obtained largely from various geologic and hydrologic reports and from individuals familiar with the area.

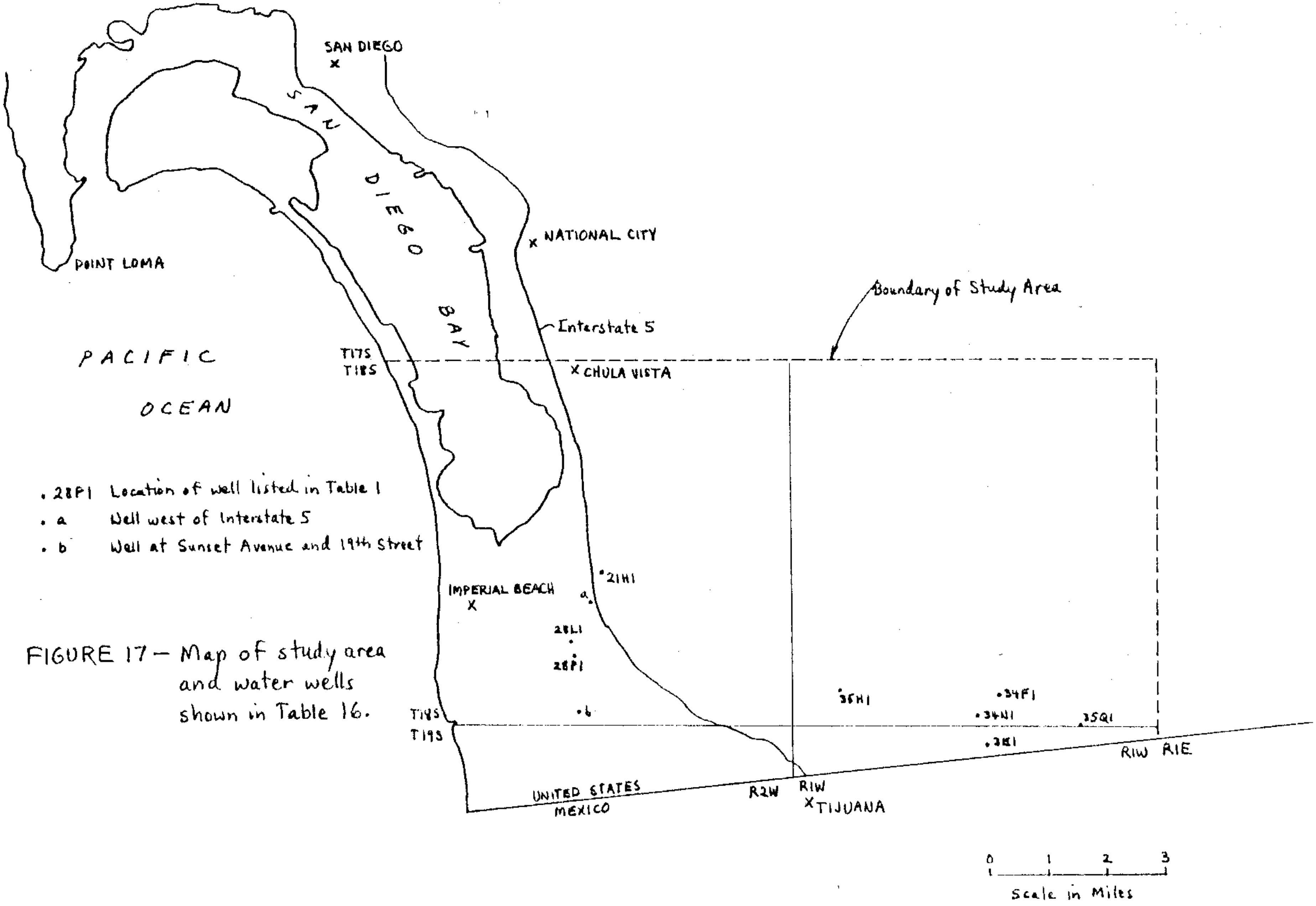

FIGURE 17 — Map of study area and water wells shown in Table 16.

STRATIGRAPHY

The stratigraphy of the San Diego area consists of Mesozoic plutonic and metamorphic basement overlain by marine and non-marine sediments of Cretaceous, Tertiary, and Quaternary age. Figure 18 is a generalized geologic map of the area; for more detail, the reader is referred to Kennedy's (1977) geologic map. It should be emphasized that the Tertiary units are still undergoing both refinement and correlation with units elsewhere.

The oldest known rocks in the study area are the Santiago Peak metavolcanic rocks of Upper Jurassic age. These have been intruded by plutonic rocks composed predominately of granodiorite. East of the study area, these basement rocks form the bulk of the Peninsular Ranges, but within the study area they are largely buried under younger sediments. The different depths at which these rocks have been found in boreholes lend support to Peterson's (1970) belief that the topographic surface upon which the younger sediments were deposited was one of substantial local relief. It appears from evidence in boreholes that the depth to basement increased from east to west; basement is encountered in several water wells on Otay Mesa at less than 450 meters, whereas two boreholes in the coastal plain to the west have encountered basement at 1680 meters.

Proceeding up-section, Cretaceous marine sedimentary rocks do not crop out in the study area, but have been found in several exploratory wells at depths of up to 1680 meters. Kennedy (1977) has mapped an Eocene unit of marine sandstone (Mission Valley Formation) that crops out in the lower Otay Valley. Kennedy interprets an unnamed fanglomerate in the upper part of the valley to be younger than this unit. Overlying the fanglomerate is the recently-defined Otay Formation, which is composed of sandstone and claystone, the latter largely bentonite. Both Artim and Pinckney (1973) and Kennedy (1977) consider this formation to be Miocene. Above the Otay is the Pliocene San Diego Formation,

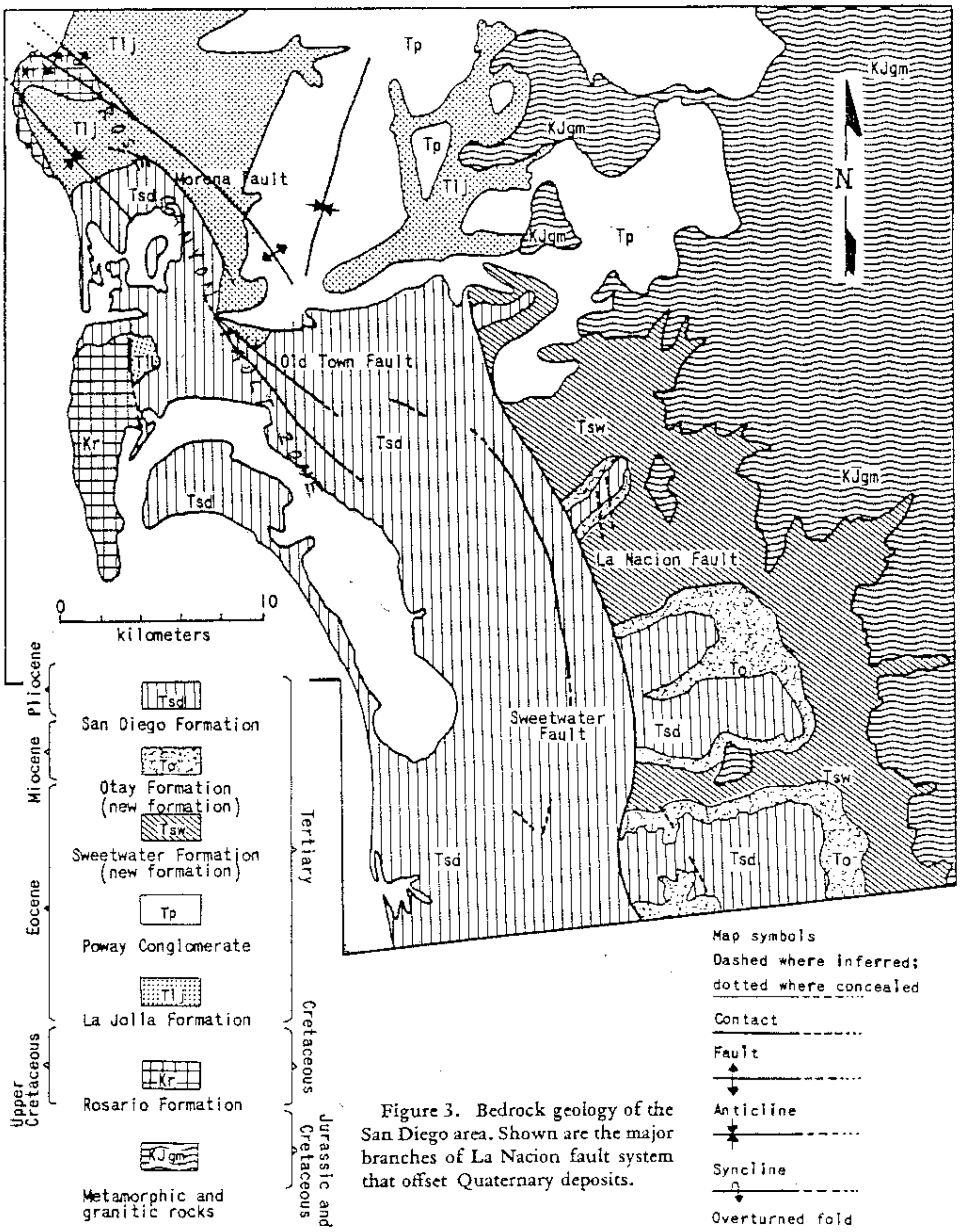

Figure 3. Bedrock geology of the San Diego area. Shown are the major branches of La Nacion fault system that offset Quaternary deposits.

FIGURE 18 – Generalized geologic map of the San Diego area from Artim and Pinckney (1973).

which consists predominately of marine sandstone and some conglomerate. Two Pleistocene terrace deposits overlie the San Diego Formation: the Lindavista Formation and the younger Bay Point Formation. Various alluvial deposits complete the section. The maximum thickness of the Cretaceous and Cenozoic sediments, estimated from boreholes, may be on the order of 1830 meters.

STRUCTURE

Over the past decade, numerous faults have been recognized in the San Diego region; more are being recognized as detailed mapping continues. The two most important fault zones are the Rose Canyon and La Nacion, both of which are shown in a generalized way in Figure 18. Wiegand (1970) postulated that the Rose Canyon fault zone is a segment of a large fault system that includes both the Newport-Inglewood zone, over 100 km to the northwest, and an active zone in Mexico, southeast of Tijuana. This hypothesis requires that the Rose Canyon fault zone continue through San Diego Bay and southeast to Tijuana, approximately parallel to Interstate 5. This continuation represents a structural low, or graben; faults west of San Diego Bay generally have dip-slip motion down to the east while faults east of the bay, including La Nacion fault, have dip-slip motion down to the west.

The predominant trends of the faults in the San Diego region appear to be both northerly and northwesterly; a few trend east-west. Fault planes dip moderately to steeply, and motion is generally normal dip-slip, although Moore and Kennedy (1975) believe that right-lateral strike-slip movement may have occurred on some faults. Ziony and Buchanan (1972) reported offset of the Lindavista Formation, and Kennedy _et al_. (1975) reported offset of the Bay Point Formation. Artim and Pinckney (1973) reported offset of Holocene alluvium by

La Nacion fault, although Elliot and Hart (1977) dispute this Holocene activity. Of significance is Artim's and Pinckney's (1973) observation that borings about 30 meters deep in sedimentary rocks around the San Diego area showed that fractures in those rocks are open. This suggests that the area is undergoing tensional forces. Such forces may be important in dilation of the faults in the area, thus allowing deep circulation of ground water.

Plate 3 shows faults mapped or interpreted by Kennedy et al. (1975) in a large portion of the study area. A few inferred faults are shown in the area of some thermal wells southeast and east of Imperial Beach, but these do not appear to coincide with the wells. It may be that the waters are rising along as yet still-unrecognized faults. The same may be true of thermal wells situated on top of Otay Mesa.

In regards to folding of the Cretaceous and Cenozoic strata, nearly all dips mapped by Kennedy (1967, 1977) of strata in the coastal area are less than 15°. In some instances, however, drag along faults has produced moderate dips in the adjacent strata.

HYDROLOGY

(Drawn largely from CDWR Bulletin 106-2, thus data is available only up to 1967).

The study area is composed of three hydrologic units. From north to south these are: Sweetwater, Otay, and Tia Juana. Each is named for the major river that drains it.

As of the middle 1960's, the most abundant source of ground water in the three river valleys was unconsolidated alluvial deposits; the underlying Cenozoic sediments were also an important source. In the areas of alluvium, the water table generally occurred at depths of 8-15 meters below the surface of the ground. Depths to water on the nearby mesas were generally greater than 152 meters because of the higher positions of the mesas relative to the floors of the river valleys. About half of the wells within Holocene and Pleistocene sediments produced between 1900-3800 liters/min.

Deterioration of water quality over the years has resulted from periods of low precipitation combined with overdraft of the water table. In some of the coastal valleys, water levels have been drawn down as much as 15 meters below sea level. Consequently, sea water and connate water, both with high total dissolved solids (TDS), have infiltrated the ground water.

Sweetwater Unit

Depths of wells in alluvium of the Sweetwater Valley are generally less than 15 meters; in the underlying Tertiary sediments, some wells extend to more than 305 meters. Water from the alluvium was of inferior quality because of high TDS, which was probably associated with intrusion of sea water or connate water. Water from the Tertiary sediments was of marginal to good quality.

Otay Unit

Ground water was produced mainly from Tertiary sediments with minor production from alluvium; water from the former was considered to be connate. Depth to water in the Tertiary sediments was generally greater than 31 meters, and most wells reached depths between 91 and 244 meters. Water was of marginal to poor quality because of high TDS.

Tia Juana Unit

Ground water was produced mainly from alluvium that underlies the valley floor and from Tertiary sediments that underlie the adjacent mesas. Depths to water in the alluvium were generally less than 15 meters and most wells were between 9 and 31 meters deep. Depths to water in the mesa area were generally more than 31 meters and many wells were between 244 and 427 meters deep. A high content of sodium and calcium in the water of the mesa area was attributed to its apparent connate character. Wells in alluvium of the coastal plain were degraded because of intrusion of sea water.

EVIDENCE OF GEOTHERMAL HEAT

Many lines of evidence or lack thereof are discussed below to illustrate the geothermal regime of the study area.

Heat Flow

Based on admittedly few borehole measurements, Sass *et al.* (1971) have classified the entire south coastal area of California, including the San Diego area, as one of *low* heat flow (1.5 HFU). In the local area, apparently no heat flow measurements have been taken. Those reported by Sass *et al.* (1971) were in the Peninsular Ranges and farther east.

Volcanism

Except for intercalated layers of bentonite (altered volcanic ash) in the Miocene Otay Formation, there are no known Cenozoic volcanic rocks in the study area. Minch (1967) has mapped extensive Mio-Pliocene basalt in Baja California as close as about 3 km from the U.S.-Mexico border, however. Within the study area, there are no known high-temperature thermal springs, geysers, or fumaroles suggestive of volcanic activity.

Seismicity

The entire San Diego coastal area is remarkably quiet seismically, even though zones of high seismicity border it on the northwest, east, and south (Figure 19). Only a few felt earthquakes and no epicenters associated with earthquakes of magnitude 4 and greater have been recorded in the area for

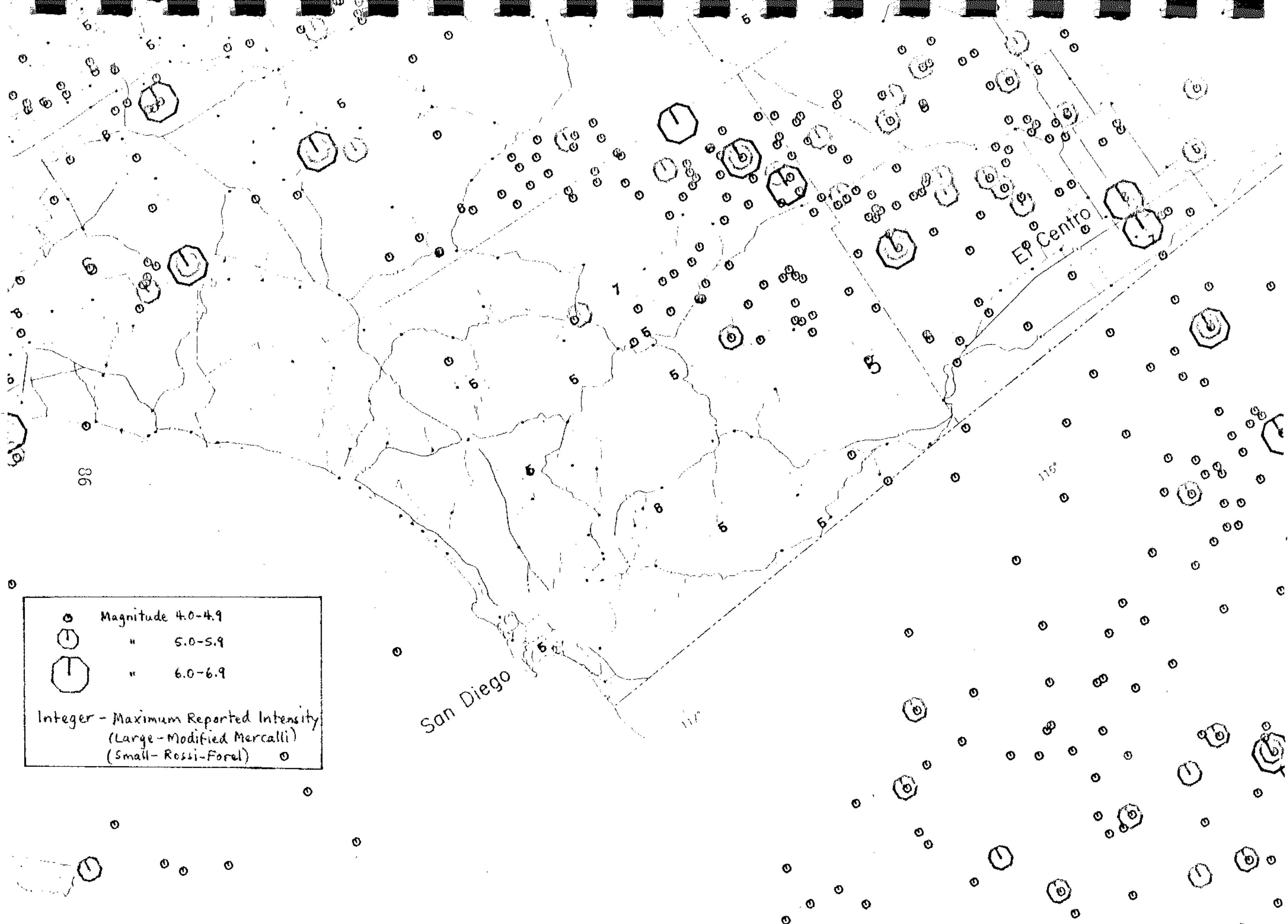

FIGURE 19—(From Calif. Div. Mines and Geology Map Sheet 39, 1978)

the period 1900-1974 (California Division of Mines and Geology, 1978).

Thermal Springs

The nearest reported thermal springs are in the city of Tijuana (Wiegand, 1970), which is just across the U.S.-Mexico border from San Ysidro. Data on these were not found during a search of the literature. CDWR Bulletin 106-2 mentioned possible thermal springs between Sweetwater and Loveland Reservoirs, about 20-30 km northeast of the study area, but gives no information on them. Kathe Bertine of San Diego State University (personal communication, 1979) mentioned that a search of old literature found evidence for a thermal spring at Point Loma, which is northwest of the study area (Figure 17). Keith Johnson also at San Diego State (personal communication, 1979), reported many thermal springs in the Ensenada area of Baja California, about 75-100 km southeast of Tijuana. He noted that the temperatures of the springs decrease as the topographic elevation increases. Johnson attributes this to a thickening of the Earth's crust, such that the thermal waters have to move a farther distance from their source of heat. Finally, he observed that hydrogen sulfide is a prominent constituent of most of the thermal springs and is probably derived from leaching of sulfides and sulfates in the wall rock.

Thermal Wells

Don Lande of the California Division of Oil and Gas (personal communication, 1979) reported that no exploratory geothermal boreholes have been drilled in the study area. He also stated that Rohr Industries Incorporated of Chula Vista wanted to drill a well for geothermal space heating about 1978, but has done nothing on the matter since.

Eleven exploratory wells for oil and gas have been drilled in the study area. Figure 20 shows both the location and pertinent data of each well.

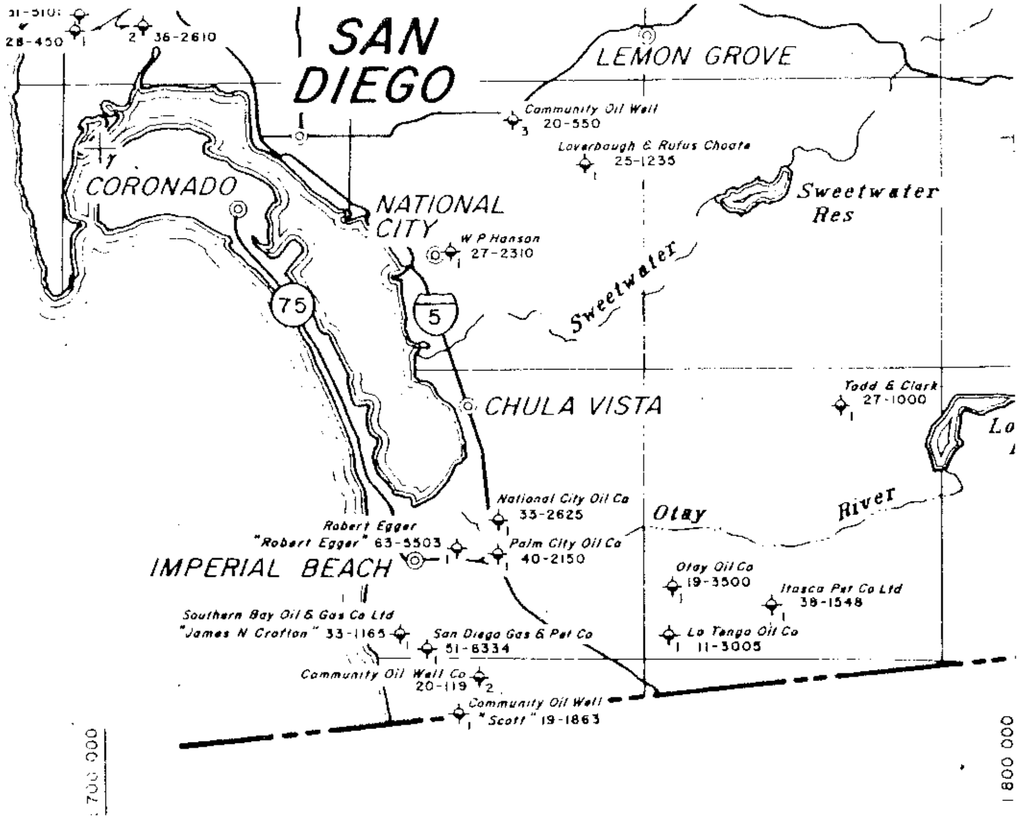

FIGURE 20

Data on exploratory oil and gas wells in the south bay area of San Diego County.

Source of data: Calif. Div. Oil and Gas, 1964

The Robert Egger 1 had a recorded temperature of 140°F at 5503 feet.

San Bernardino B. & M.							Total	
T.	R.	Sec.	Operator	Well No.	Elev. (feet)	Date started	depth (feet)	Stratigraphy (depth in feet) Age at bottom of hole
17S	2W	11	L. Overbaugh & Rufus Choate	1	350	Oct. 1924	1240	Pliocene
		23	Community Oil Well	3	175	April 1920	550	Pliocene
		23	W. P. Hanson	1	290	April 1922	2310	Eocene
18S	2W	21	Robert Egger	"Robert Egger" 1	14	Oct. 1962	5503	Weathered granite 4950; Basement (granite)
18S	2W	21	Palm City Oil Co.	1	50	Jan. 1938	2150	Pliocene
		22	National City Oil Co.	1	50	April 1924	2625	Pliocene
		31	South Bay Oil & Gas Co., Ltd.	"James N. Crofton" 1	10	April 1931	1165	Pliocene
		32	San Diego Gas & Pet. Corp.	1	17	March 1934	6334	L Pliocene 300; Eocene 2900; Cretaceous 3900; Basement (volcanics) 5529
18S	1W	6	Todd & Clark	1	320	July 1924	1000	Pliocene
		30	Otay Oil Co.	1	385	Jan. 1910	3500	Cretaceous
		31	Le Tengo Oil Co.	1	400	Oct. 1911	3005	Cretaceous
		33	Itasca Petroleum Co., Ltd.	1	520	May 1931	1548	Cretaceous
19S	2W	4	Community Oil Well	2	20	Dec. 1919	119	L Pliocene
		9	Community Oil Well	"Scott" 1	325	pre-1916	1863	Cretaceous

Only one, the Robert Egger 1 drilled in 1962, has a recorded bottomhole termperature. All of the others were drilled prior to 1940, before temperature-logging techniques were developed. The temperature of the Robert Egger 1 was 60° C (Don Lande, personal communication, 1979), which is not considered thermal. If a mean ambient temperature of 16° C is assumed, computation produces a crude geothermal gradient of less than 1° C/31 meters.

Discussions with local drillers did not produce supplemental data on the study area. A decrease in urbanization, importation of water from elsewhere, and deterioration of the quality of the ground water all have forced drillers to move out of the area or go out of business. A brief review of drillers' reports at the Department of Water Resources Office in Los Angeles revealed only three wells that have been drilled since 1967. Most wells were drilled in the 1950's and many are now abandoned, especially those on Otay Mesa where imported water is used for irrigation and domestic purposes.

CDWR Bulletin 106-2 is the best single source of data on the numerous water wells in the study area. Although much of its information is outdated, it does provide data on temperatures and chemistry of the ground waters. Temperatures for water wells listed in Bulletin 106-2 range from the high teens to 36° C. Most temperatures are in the high teens and low 20's degrees Centigrade. Wells of about 27° C and above are considered to be significantly warmer than "average" and can be important clues in the search for water of sufficient temperature for direct uses. Data from Bulletin 106-2, from the records at the DWR office in Los Angeles, and from Wiegand (1970) on these thermal wells are presented in Table 16; locations of the wells are shown in Figure 17. As can be seen from Figure 17, there are two areas of thermal wells, one east and southeast of Imperial Beach and the other on Otay Mesa.

Table 16. Thermal and chemical data from water wells in the South San Diego Bay area (Data from CDWR Bulletin 106-2, records from CDWR office in Los Angeles, Wiegand (1970), personal communication).

WELL NUMBER OR LOCATION	TEMPERATURES REPORTED IN °F	pH	SPECIFIC CONDUCTANCE (μmhos at 25°C)	CHEMICAL CONSTITUENTS IN PARTS PER MILLION												WELL DEPTH (feet)	PRODUCTION ZONES	COMMENTS
				Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	F	B	SiO_2	TDS			
18S, 2W, 21H1 200 ft. east of I-5	82	8.0	2150	148	64	230	4	146	99	644	2.5	0.2	0.07	13	1608	600		
18S, 2W, 28L1S Near Grove and 19th	80	7.5	4371	226	121	547	6	341	213	1230	25.0	0.6	0.42	33	3002			High Na, Cl content may be caused by intrusion of sea water.
18S, 2W, 28P1S Near Grove and 19th	97 (DWR 106-2) 103 (Drill Report) 110 (Wiegand, 1970)	7.9	1730	32	31	316	-	323	169	298	1.6	0.8	0.38	--	~1200	1735	1700-1735 ft. Pre-Quaternary sediments	Owned and operated by Robert Egger, a dairy farmer, who uses the water for washing down his dairy cows.
300 ft. west of I-5 on Palm Avenue	80															200		
Intersection of Sunset Avenue and 19th Street	90 (Wiegand, 1970) 96 (R. Egger, pc 1979)															1412		
18S, 1W, 31H1S Otay Mesa	91	7.2	2266	42	1	437	16	43	104	700	0	2.1	0.70	18	1473	1150	800-1140 ft. Pre-Quaternary sediments	Producing zones overlain by about 70 feet of clay. This well and those below probably produce connate water (moderate Na, Cl content). These are also high in boron and fluorine. Magnesium unusually low.
18S, 1W, 34N1S Otay Mesa	83	7.1	2080	54	1	391	2	49	43	651	0.2	2.6	1.07	200?	1314	1415	850-1375 ft. Pre-Quaternary sediments	DWR records report SiO_2 as 99.9 ppm; unusually high as no other well in this region has SiO_2 content near this amount.
19S, 1W, 3E1S Otay Mesa	83	7.9	2070	69	0	363	4	27	79	613	1.4	4.9	0.97	18	1213	1402	1045-1360 ft. Pre-Pliocene sediments	Bentonite reported at 309-359 feet (Otay Formation? Hot water reported at 1145 ft.; warm water reported at 1284 ft.
18S, 1W, 35Q1S Otay Mesa	85															1197	600-1124 ft. 1170-1180 ft. Pre-Quaternary sediments	Plutonic bedrock reported at 1174 ft.
18S, 1W, 34F1S Otay Mesa	79	8.0	1630	35	0	360	9	30	81	534	0	3.0	1.08	12	984	1374	1050-1365 ft. Pre-Quaternary sediments	Possible basement (slate) at 1365 ft.

The warmest well is that at the intersection of 19th Street and Grove Avenue (see Plate 3). Robert Egger, whose father had the well drilled, said this well was about 39° C, although CDWR Bulletin 106-2 reported a temperature of 36° C. Egger also stated that the well is artesian. Unfortunately, the log books for this well were reportedly stolen, consequently, the driller's report has gaps in it. The highest recorded temperature in the thermal area on Otay Mesa was 33° C in a well that is now abandoned.

Geophysical

Kennedy et al. (1975, 1977) performed geophysical surveys in the Otay and Tia Juana River Valleys to investigate subsurface geologic structure. The locations of traverses discussed in the 1975 publication are shown in Figure 21, profiles for three of the traverses are shown in Figure 22. Of possible significance on traverse MI-MI' is the anomaly M-8, which coincides with the thermal well at Sunset Avenue and 19th Street.

Geochemical

Sampling of water from wells in the study area for chemical constituents has been extensive because of concern about the degradation of water quality over the years. For our purposes, these chemical data are potentially useful either as a measn of determination of the source of the water or as a means of estimation of the temperature of the water at its source (geothermometry).

Wiegand (1970) suggested that the chemical constituents of several of the thermal wells listed in Table 16 were evidence for a "geothermal source." What he meant by a "geothermal source" is not clear. CDWR Bulletin 106-2 noted that thermal springs in the San Diego region were characterized by relatively high concentrations of fluoride, boron, sodium, chloride, and sulfate. It was assumed that these thermal waters rose from great depths along faults and mixed both vertically and laterally with shallow ground

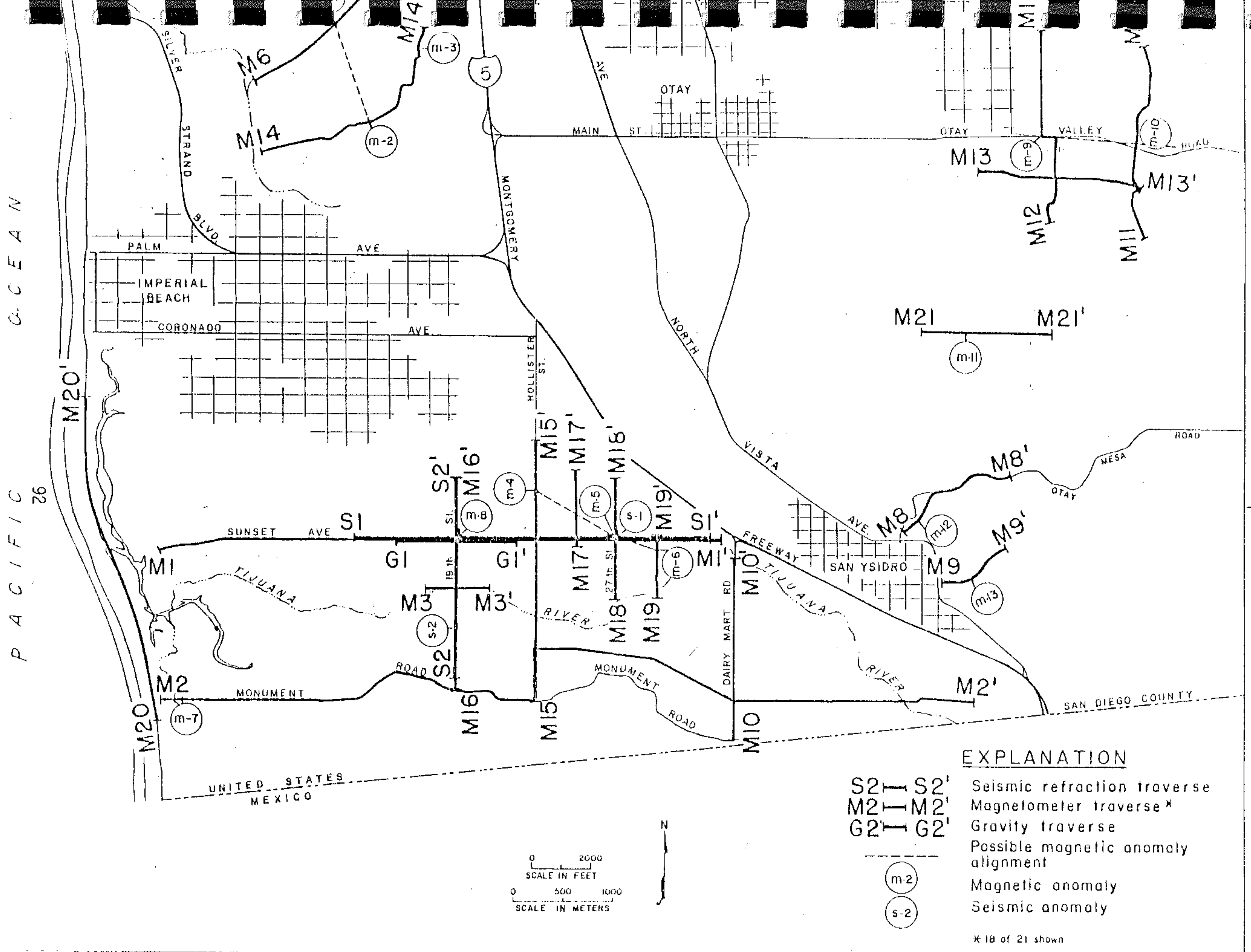

FIGURE 21

Index map showing locations of seismic, magnetic and gravity traverses. From Kennedy *et al* (1975).

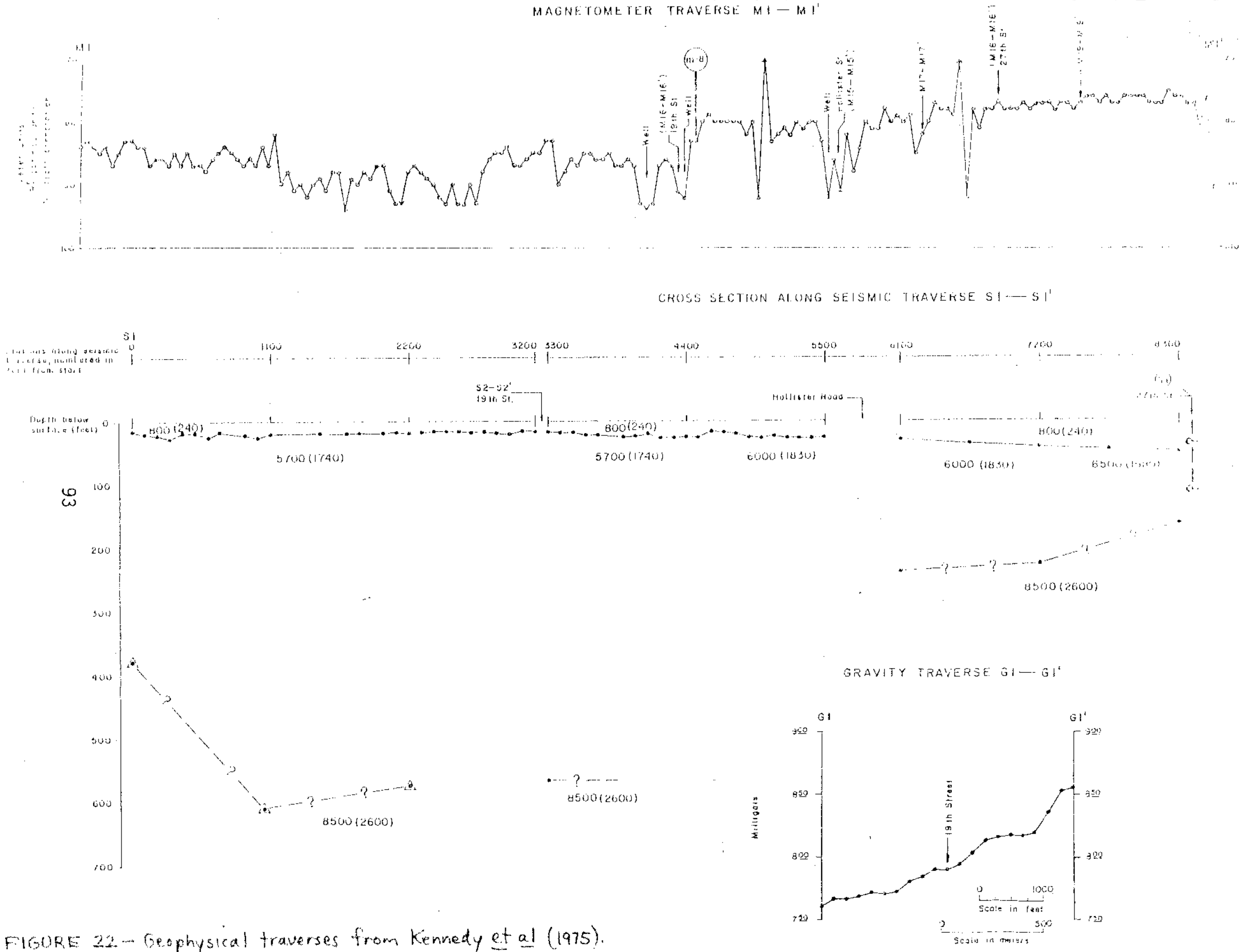

FIGURE 22 – Geophysical traverses from Kennedy et al (1975). Locations of traverses shown on Figure 21.

water of meteoric origin. Within the study area, however, much of the ground water is connate (probably trapped sea water in many cases) or is meteoric water intruded by sea water. Both the connate water and sea water typically have high concentrations of sodium and chloride, so these constituents may not be reliable indicators of water that has circulated at great depths. Either separately or in combination, the other constituents, fluoride, boron, and sulfate, in addition to silica, may be useful indicators of water of deep circulation, depending upon local conditions and history of the ground water. For example, four of the thermal wells on Otay Mesa had unusually high concentrations of both fluoride and boron; well 35NI had by far the highest recorded concentration of silica in the San Diego region. Also of note is the peculiar absence of magnesium in these waters. Chemical concentrations in the coastal valley area west of Otay Mesa were more sporadic and have been affected by mixing, thus interpretation is more difficult. Clearly, use of chemical constituents as indicators of the sources of the thermal waters is rife with complexities.

Herbert (1977) performed a geothermometric analysis of nearly all of the area covered by the present study. He took the concentrations of sodium, calcium, and potassium for all pertinent wells listed in CDWR Bulletin 106-2 and, using Fournier's and Truesdell's (1973) formula for the Na-Ca-K geothermometer, calculated subsurface temperatures of the ground water. He then plotted these on a base map and contoured the temperatures at intervals of 10° C. His contour map is presented as Plate 4. It reveals an unusual northeast-trending pattern of alternating thermal highs and lows. The linear thermal highs may or may not correspond with unmapped faults. One of these thermal highs reaches nearly 200° C and projects northeastward from the mouth of the Tia Juana River.

Correlation of the thermal highs with locations of the thermal wells is good in some cases, poor in others. The 33° C thermal well on Otay Mesa corresponds well with a thermal high, although data there are sparse. The thermal well on Palm Avenue falls in a "cool" zone. The warm wells in Sections 28 and 33 along 19th Street appear to correlate moderately well with the thermal tongue along the mouth of the Tia Juana River.

Herbert's work is hindered somewhat by his lack of data in some places, and because he did not consider probably mixing of waters of different sources. Also, the formula of Fournier and Truesdell has since been refined to take magnesium into account. Nevertheless, it is this type of basic study that should provide a foundation for analysis of geothermal reservoirs.

EXPLANATION OF THE GEOTHERMAL HEAT

The characteristics of the crust and mantle under the San Diego area are largely unknown. The causes of the warm water temperatures in the area are therefore speculative. Three possible explanations are briefly discussed:

Heat From Decay of Radioactive Elements

Keith Johnson (personal communication, 1979) considered and rejected decay of radioactive elements as a source of heat for the thermal springs in northern Baja California. He feels that the continental crust in that area is too thin to contain appreciable radioactive material. Because of its proximity to the basin of the Pacific Ocean, the crust beneath the San Diego area may also be too thin to contain enough radioactive material to account for the thermal wells there. Also, the low regional heat flow suggests no anomalously high radioactivity. Nonetheless, because of our ignorance of the local subsurface crustal geology and local heat flow, it is unwise at this point to rule out radioactive decay as a source of the anomalous heat.

Body of Molten Material

The youngest volcanic rocks in the coastal region are Mio-Pliocene in age and, according to Minch (1967), probably had a western source in the continental borderland. It is possible that a body of molten or partly-solidified igneous material may underlie a part of the study area and could thus supply both heat and possibly a small amount of fluid to the meteoric ground water. Two pieces of evidence do not support the existence of this material, however. First, there is no evidence (lava flows, volcanoes, hypabyssal rocks, geysers, high-temperature thermal springs, or fumaroles) at the Earth's surface of any recent or current igneous activity. Second, heat flow in areas of igneous activity is generally high, whereas it is thought to be low in this area. As with the decay of radioactive elements, however, igneous activity at depth should not be dismissed until further data indicate otherwise.

Deep Circulation of Fluids

Keith Johnson (personal communication, 1979) believes that the thermal springs in northern Baja California derive their heat from geothermal gradient alone and not from bodies of molten material. His hypothesis is summarized as follows: Northern Baja California is undergroing tension, as is indicated by its extensive system of large normal faults; nearly all of the observed thermal springs are associated with such faults. Meteoric water migrates downward along the dilated fault planes to depths on the order of 5-8 kilometers. There it is heated by the geothermal gradient, whence it eventually returns to the Earth's surface via fault planes to form thermal springs. One measurement of heat flow taken several tens of kilometers southeast of the Ensenada area was about 1 HFU. Many measurements of heat flow taken off the nearby coast in the Pacific Ocean yielded an average value of about 2 HFU for that area.

It is concluded, based upon these measurements, that heat flow, and correspondingly the geothermal gradient, in the Ensenada area is low to moderate. At depths of 5-8 km, this gradient is sufficient to provide heat for the meteoric waters that feed the thermal springs.

Because of proximity and similar geologic conditions, Johnson's hypothesis may apply to the south bay area of San Diego. The area has numerous normal faults and the warmest water temperatures are found near the center of the postulated structural low that runs southeast of San Diego Bay to Tijuana. Wiegand (1970) raises an important question, however, as to why thermal wells appear to be few or absent north of the Otay Valley.

CONCLUSIONS AND RECOMMENDATIONS

The south bay area of San Diego County holds significant promise as a source of low-temperature geothermal heat. Although Herbert's (1977) study suggests reservoir temperatures of nearly 200° C, it is probably wise at this point to assume that temperatures of 30°-40° C are the highest economically-obtainable. Water wells are generally less than 450 meters and have not produced recorded temperatures higher than 33° C except for the Robert Egger well (19th Street and Grove Avenue), which had reported temperatures of about 38° C at a depth of 518 meters.

It appears that deep circulation of ground water along faults is the source of the anomalously warm waters present in many wells. Present evidence suggests that the most favorable areas for discovery of the warmest waters are in two zones, one south and east of Imperial Beach and the other under Otay Mesa. Urban development is most extensive in the former, whereas the latter is largely rural with scattered small farms and some residences.

Except for Herbert's (1977) calculations of subsurface temperatures, no study or exploration of the geothermal potential of this area have been conducted. Professors Bertine (geochemistry) and McKeon (geophysics) of San Diego State University expressed interest about possible collaboration with the Division of Mines and Geology on such studies. As the area is in their own "backyard" and because independent research projects are required of students at SDSU, both the technical knowledge and manpower would be available.

Should the study continue, specific work must include the following:

1) Careful study of all records of the numerous water wells in the area. Locations, lithologic and hydrologic characteristics of aquifers, notes by drillers, depths of aquifers, chemistry, rates of flow, recorded temperatures, and histories of the wells, all deserve scrutiny and tabulation. Unfortunately, many of the wells are abandoned, thus important sources of data may no longer be available.

2) In-depth geothermometric studies on the ground water with use of the newest formulae and techniques available.

3) Geophysical work to determine subsurface structure and heat flow. The data of Kennedy _et al_. (1975, 1977) could provide a foundation for such work.

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THE PASO ROBLES GEOTHERMAL AREA AND OTHER GEOTHERMAL FEATURES OF THE SOUTHERN COAST RANGES.

Low-and moderate-temperature geothermal resources are present in several places in the southern Coast Ranges of California. All are marked by thermal springs and/or thermal water wells and may be sufficient local sources of heat energy for the future. At present, the Paso Robles area appears to be the most significant of these sources.

GEOGRAPHY

The southern Coast Ranges of California form a system of parallel ridges and valleys that extends from Monterey Bay southeastward to Santa Barbara County, a distance of about 200 km. The ranges are bound on the west by the Pacific Ocean and on the east by the San Joaquin Valley. Summit elevations reach 600 m to 1200 m, while valley floors range from near sea level at Monterey Bay to about 450 m at the southern end of the range. There is little or no coastal plain along this section of the coast, and sea cliffs are formed where the ranges intersect the coast. In addition, the ridges and valleys along the coast provide good exposures of the structure and allow development of prominent headlands and inlets (Oakeshott, 1960). Several elevated wave-cut terraces, mostly Pleistocene in age, are also present along the coast.

The predominant topographic feature of the region is the Salinas Valley, which extends nearly the length of the Coast Ranges and separates the Santa Lucia Range on the west from the Gabilan Range on the east. The drainage pattern generally follows the northwest-trending direction of the ranges, but many small streams flow at sharp angles to this trend. The Salinas River is the dominant drainage channel, carrying run-off to Monterey Bay.

CLIMATE

The climate of the region is mediterranean, characterized by warm, dry summers and cool, wet winters. In general, the northern portion of the province has more contrast between winter and summer than the southern region, and the entire coast is subject to frequent fog. Snow is uncommon at the lower elevations, but rainfall is common and of varying amounts, depending on location and elevation. Precipitation ranges from 5 inches per year at the margin of the San Joaquin Valley to over 50 inches locally in the Santa Lucia Range south of Monterey.

REGIONAL GEOLOGY

The geology of the southern Coast Ranges is dominated by two types of basement,a northwest-trending granitic-metamorphic complex, termed the Salinian Block, and the Franciscan Complex, which consists of Jurassic-Cretaceous sedimentary, metamorphic, and volcanic rocks. The Salinian Block is bounded on the northeast and southwest by the Franciscan Complex, as shown in Figures 23 and 24. A third important group of rocks, the Great Valley Sequence, composed predominantly of Cretaceous marine sedimentary rocks, is associated with both complexes discussed above.

The age of the metamorphic rocks in the Salinian Block is unknown, but poorly preserved fossils suggest a Paleozoic age (Page, 1966). The granitic rocks, on the other hand, have been dated as Late Cretaceous and are not only younger than the metamorphic rocks, but are also younger than some Franciscan rocks. The granitic rocks occur as plutons in the Salinian Block and are exposed in the Santa Lucia, La Panza, and Gabilan Ranges.

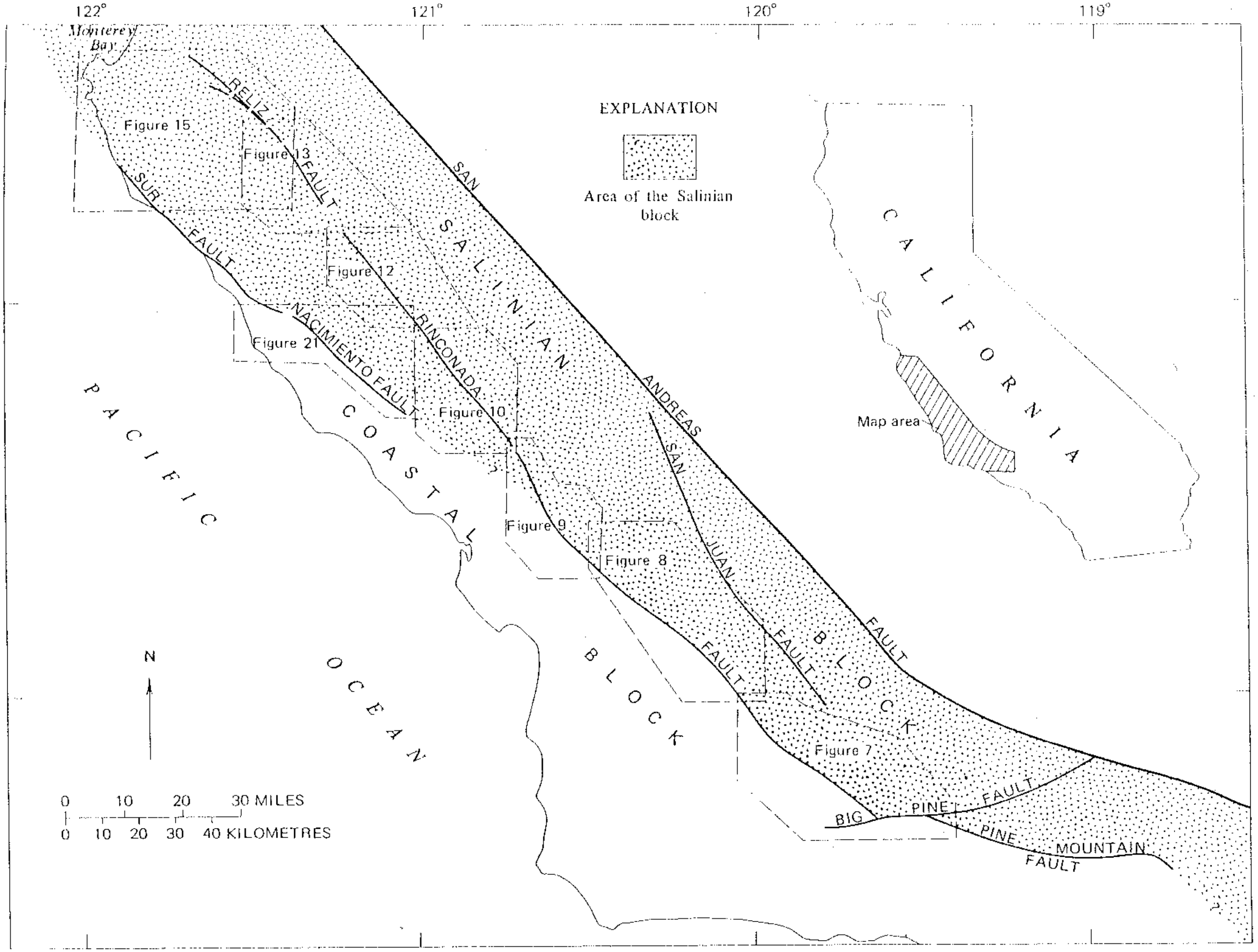


FIGURE 23 — Positions of the Rinconada and Reliz faults relative to the Salinian block and the San Andreas fault. White areas underlain by Franciscan Complex. After Dibblee (1976).

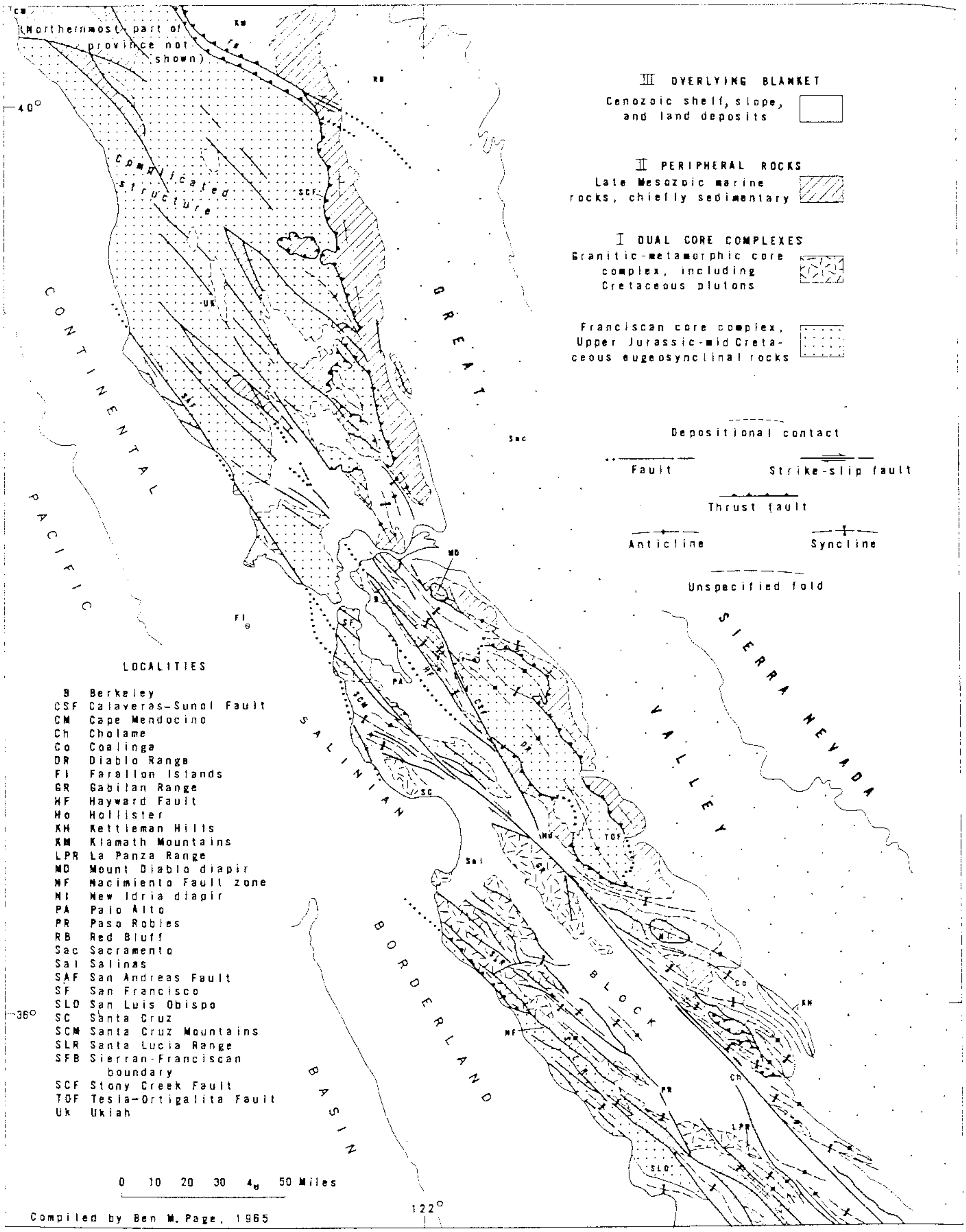


Figure 24-Tectonic map of the California Coast Ranges.

The Franciscan Complex is believed to represent ocean-floor sediments and volcanic rocks that were scraped off against an overriding edge of the North American plate during Andean-type subduction. Fossils within the Franciscan have been dated as Late Jurassic to Early Cenozoic. Most of the Franciscan is composed of graywacke sandstone.

The southern Coast Ranges are blanketed by Tertiary and Quaternary marine sedimentary formations, which are usually discontinuous in lateral extent due to orogenic interruptions and subsequent erosion. The oldest Tertiary rocks, which are shallow marine sandstone, conglomerate, and shale of Paleocene Age, crop out only in small, local areas. Eocene rocks, on the other hand, consist of sandstone and mudstone composed of turbidite sediments deposited at depths ranging from littoral to bathyal. Fossil remains indicate a period that was warmer and moister than the rest of the Tertiary. Much of the Oligocene record has been lost to erosion, but it can be found locally as marine shale and sandstone, interfingering with submarine basalt flows and tuff. Nonmarine Oligocene strata are also found in the region.

From Eocene to Miocene, the region consisted of lowlands and shallow seas, with a mild climate. The lower Miocene seas were the site of accumulation of conglomerate, sandstone, shale, and limestone. The middle and upper Miocene witnessed an advance of the seas and the subsequent deposition consisted of siliceous sediments, mainly shale. Volcanic activity was also common during the Miocene, depositing flows, tuffs, and bentonite layers. The shallow seas of the Miocene continued into the Pliocene, but became more restricted in size. Rocks of this age consist of marine sediments and volcanic rocks along the San Andreas Fault zone, in the southern Gabilan Range, and in the southern Diablo Range.

The present southern Coast Range structures were formed in the late Pliocene, when the region underwent folding and faulting due to strong compressive forces. The subsequent erosion and deposition of coarse sediments over the lowlands gave rise to the continental Plio-Pleistocene formations seen today. These sediments will be more thoroughly discussed in a later section of this report.

Early Tertiary thrusting caused the emplacement of rocks of the Great Valley Sequence over the Franciscan assemblage at the east side of the region. This appears to be one of the important periods of orogeny in the Coast Ranges. Tertiary strata lying on the Franciscan basement complex is always found to be folded, while sediments on the granitic-metamorphic core complex may or may not be disturbed. Most of the structure of the Coast Range is very complex, however, because of folding and faulting during the Miocene and later. All of the great fault zones (most are still active today) were active during this period. Among these, steep reverse faults are common, especially in the Santa Lucia Range of the Salinian Block, west of Paso Robles. The motion on this system was mainly during the Pliocene and early Pleistocene. The Rinconada Fault, in particular, will be discussed in detail in the Paso Robles portion of this discussion.

HOT SPRINGS

Geothermal resources in the southern Coastal Ranges are generally low-temperature, that is, less than $90^{\circ}C$. In fact, the temperatures of most thermal springs and hot wells in the region are only slightly elevated above ambient temperature. The distribution of the resource as currently understood is shown by the locations of natural hot springs in Figure 25.

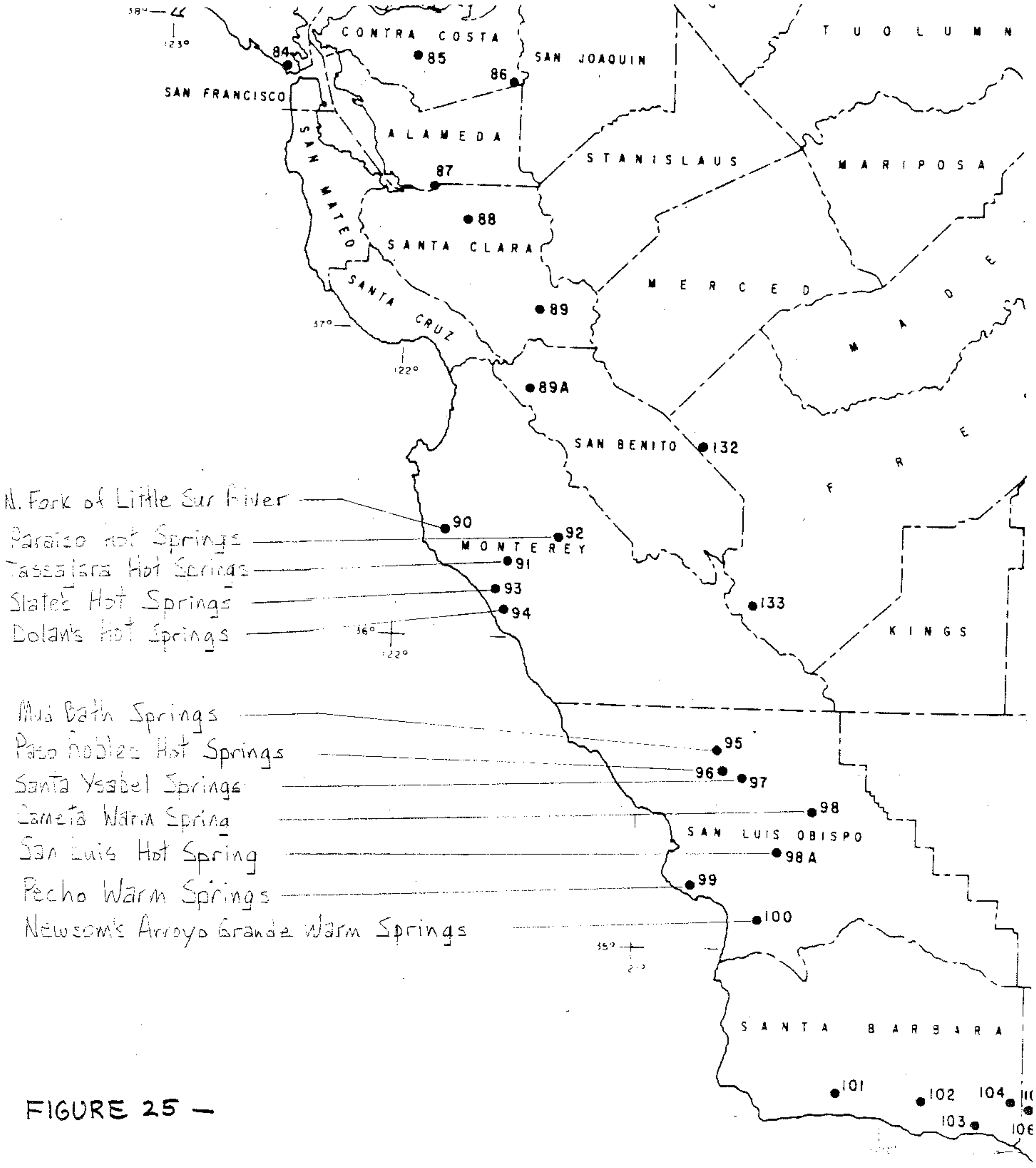


FIGURE 25 —

HOT SPRINGS OF THE SOUTHERN COASTAL RANGES

In Monterey County, thermal springs are active in five locations in the Coast Ranges. Springs on the Little Sur River, north of Big Sur, have been measured at 46°C, but have very little flow and are in a remote area of low population. Slate's Hot Springs, on the coast south of Big Sur, consists of many individual springs issuing from the sea cliff. Temperatures and flows have been documented up to 50°C and 150 l/min respectively. During the early 1900's, the water was used for a small private bathhouse. Still farther south is Dolan's Hot Spring, which is inland from the coast along Big Creek. The location is remote and flow has been reported as 114 l/min at a temperature of 37°C (Berkstresser, 1968). These three sites may have local usefulness as hot baths, but data are too limited to suggest the existence of a significantly large geothermal resource.

Monterey County also includes Tassajara Hot Springs and Paraiso Hot Springs. Tassajara, south of the town of Jamesburg, consists of springs reaching temperatures of 62° and flows of 189 l/min. These springs have been known and used for decades as a spa. At present, the area is the site of a Zen Buddhist Monastery.

Hydrogen sulfide gas is present in the water, as are high concentrations of silica. Paraiso Hot Springs, near the Salinas Valley and more accessible than Tassajara, features water of about 37°C but of low flow rate. The area has had a long history of use. It was known to the Catholic mission fathers and has been used since the 19th century as a spa. While these two areas have merit as spas, more resource assessment data are required before one could predict extensive direct use in the future. Population centers are too distant to transport the water for use.

In San Luis Obispo County, there are also numerous surface expressions of geothermal potential in the form of hot springs and hot water wells. Newsom's Hot Spring is about 4 km east of the town of Arroyo Grande, and produces water at a temperature of about 37°C. The spring has been used for bathing for over 100 years, but the temperature and low rate of flow do not indicate a large resource. Pecho Warm Springs, west of San Luis Obispo and about two miles inland, produce low volumes of 35°C water and hydrogen sulfide gas and have been used for bathing. San Luis Hot Spring, south of San Luis Obispo and near the ocean, is actually a deserted oil well that flows hot water at over 38°C. The water, high in sulfide and salinity, has been used for a spa, and a hotel exists at the site. Nearby, just east of Avila Beach, is another well that flows hot water. Known as Hidden Valley Hot Springs or Budan Spring, the temperature is over 75°C with moderate flow and has been used as a spa.

Of all the indicators of geothermal potential in the southern Coast Ranges, the Paso Robles area surpasses those already mentioned. Numerous springs and wells over a large area produce water at high flows and temperatures up to 47°C. The artesian nature of the water and moderate temperatures have made the area popular for its baths, and this region, because of its population and agrarian economy, lends itself well to the evaluation of low- to moderate-temperature geothermal resources in California.

THE PASO ROBLES REGION

BACKGROUND AND HISTORY

The Paso Robles low-temperature geothermal resource is in the southern Salinas Valley (Figure 26); it extends at least 15 km east and southeast

LOCATIONS OF CALIFORNIA KNOWN GEOTHERMAL RESOURCE AREAS (KGRA'S)

SOURCE: Jet Propulsion Laboratory, Geothermal Energy Resources In California: Status Report for ERCDC (June 1976), pp. 1-3

FIGURE 26 — Location of Paso Robles region relative to California's KGRA'S.

from the town of Paso Robles. This area occupies most of the central and eastern Paso Robles 15' quadrangle and covers an area of over 230 square kilometers. The western extent of the known hot water lies beneath the town of Paso Robles. The region of known hot water is shown by Figure 27.

The area is bordered by the Santa Lucia Range on the west and the Temblor Range on the east, both reaching elevations of over 600 m within 33 km of the town of Paso Robles. The floors of the valleys in the resource area are from 210 m to 300 m above sea level and trend north-northwest. Durham (1974) referred to the topography as a "dissected old land surface". The Salinas River at Paso Robles is the lowest point in the region of known warm water, while the highest are the hilltops 15 km to the east. The region is drained by the Salinas River, which occupies a flood plain approximately 0.5 km in width, and its tributaries, Huerhuero Creek, Dry Canyon and the Estrella River. Mean seasonal precipitation in the region for the period 1897-98 to 1946-47 is shown in Figure 28.

The low-temperature geothermal resource of the Paso Robles area has a long history of use, mainly for spas and mud baths. The natural hot springs at the present location of downtown Paso Robles provided easy access to the resource in the early days. The earliest recorded use was by the Franciscan Padres who constructed mineral baths at the San Miguel Mission in 1797 and transported warm water by an eight-mile aqueduct from the springs. The water was again put to use starting in about 1857, when the Paso de Robles Rancho was occupied, and again in the early 1860s, when the Hotel Paso Robles was opened. The area with it's hotel, spa, mud baths, and health treatments soon became one of California's most popular health resorts. Several springs were developed for use as spas, including the Main Spring in downtown Paso Robles and the Soda Spring and

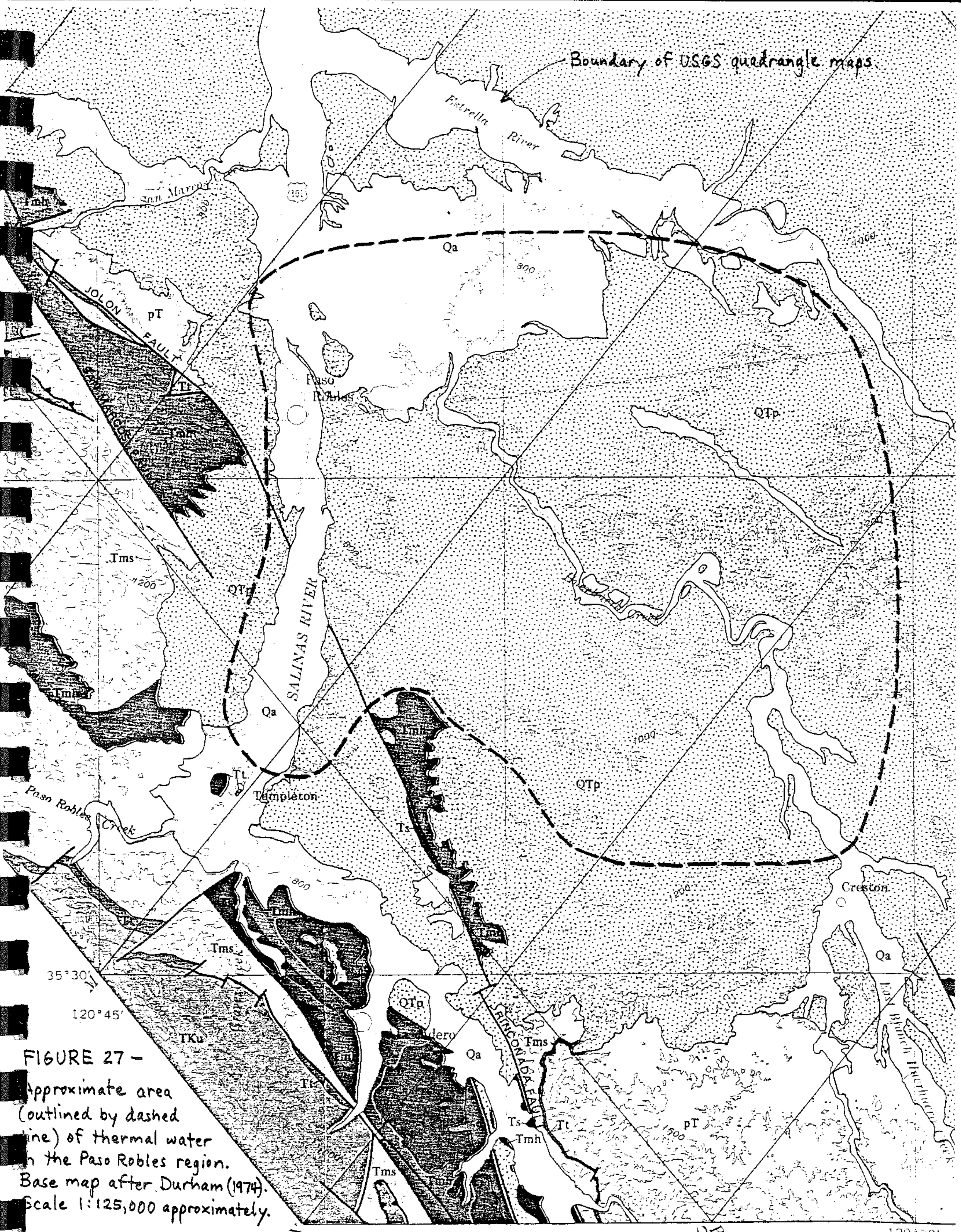


FIGURE 27 –
Approximate area
(outlined by dashed
ine) of thermal water
n the Paso Robles region.
Base map after Durham (1974).
Scale 1:125,000 approximately.

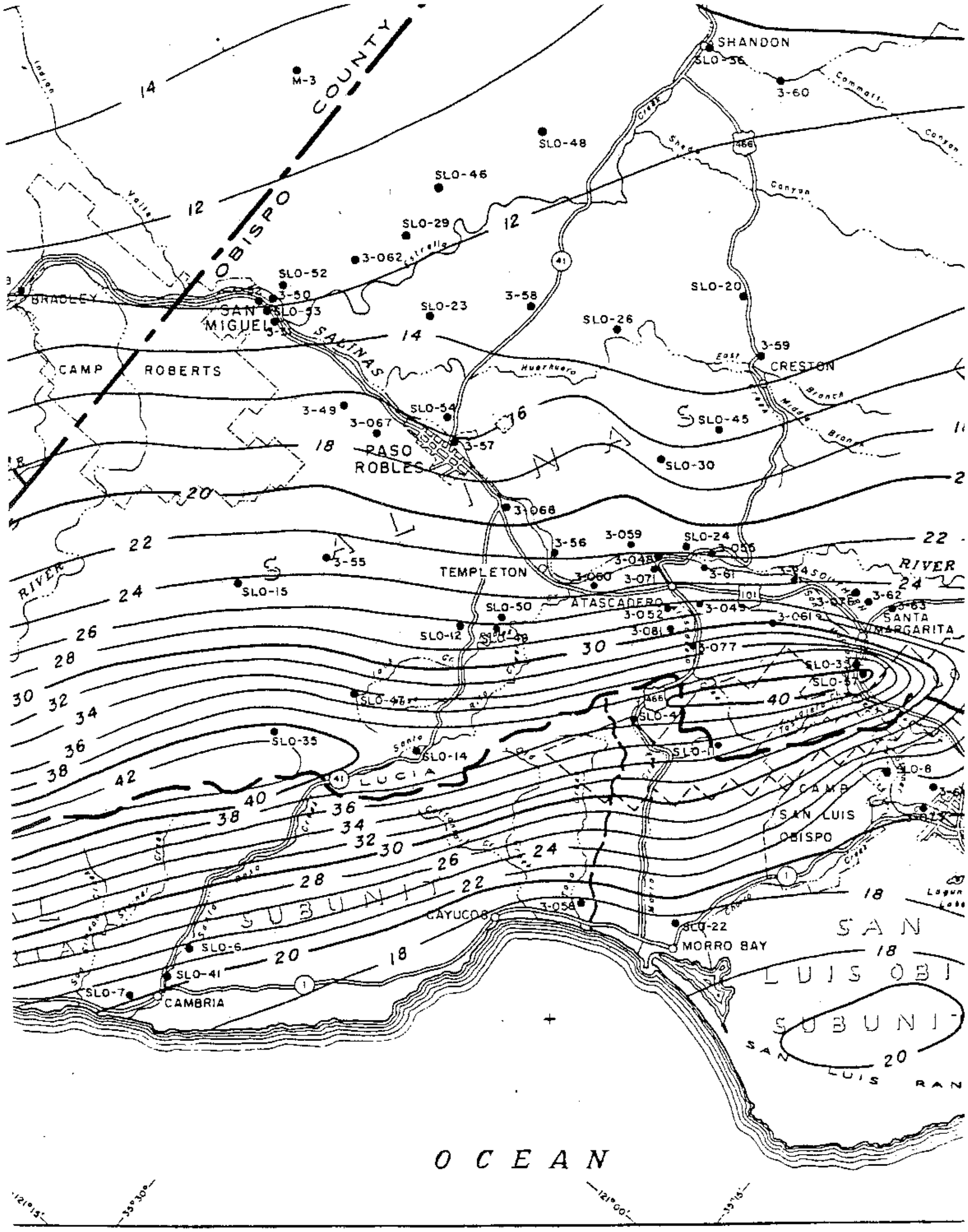


FIGURE 28 — Lines of equal mean seasonal precipitation (inches) for the period 1897-98 to 1946-47. Dots mark precipitation stations. After Calif. Dept. Water Resources (1958).

Mud Spring about 4 km north of town. A so-called plunge was built at the Main Spring site and during this period, the town was often referred to as Hot Springs.

A new hotel, El Paso De Robles, opened in 1891 with a well that reportedly flowed nearly 4 million liters per day of 49°C sulphurous water. This establishment further enhanced the reputation of the area. The new hotel became a stage stop and was served by the railroad when it was built in 1901. The hotel's location, midway between Los Angeles and San Francisco, made it an ideal stopping point.

In 1903, twelve businessmen formed the Paso Robles Hot Sulphur Water Company, drilled a well at 11th and Pine, and built a spa. The establishment later was to become the Municipal Baths and today is a realty office. The many springs and wells used during the spa perid produced water ranging from about 27°C to 60°C. Today, the popularity of the spas has waned and many of the wells have been abandoned to prevent the sulphur water from becoming a pollutant. Table 17 lists the early springs and wells in the Paso Robles area and presents chemical and physical data on them.

GEOLOGY OF THE PASO ROBLES REGION

The Paso Robles geothermal resource occupies a portion of the Salinian Block, consisting of Cretaceous granitic basement rocks separated from Franciscan basement on the east and west by the San Andreas and Rinconada Faults respectively (Figure 29). The basement in this area is commonly granodiorite, adamellite, and granite, dated in many locations as Cretaceous (70 to 89 my BP) by the K-Ar method. Metamorphic rocks, older than the Cretaceous rocks that intrude them, also occur in the Salinian basement. Two outcrops of the granite are exposed in the

Table 17. EARLY HOT SPRINGS AND WELLS; CHEMISTRY

Map No.	Name of Spring	Location	Flow	Temp °F		Ca ppm	Mg ppm	Na ppm	K ppm	SiO_2 ppm	HCO_3 ppm	CO_3 ppm	$CaCO_3$ ppm	Cl ppm	SO_4 ppm	NO_3 ppm	B ppm	odor, color	pH	mhos/cm ECX10^6 @25°C	TDS	Remarks
1	Paso Robles Hot Spring	11th and Spring Street																			1336	Original natural spring. Swimming Plunge constructed.
2	Mud Bath Spring	2½ mi. N of Paso Robles Hotel; 100 yds W of River		104 to 126		119	1.2	665	11	105		27		805	538			7.1 H_2S			2407	High in sulfate and Chloride
3	Soda Spring	75 yd NW of Mud Bath Spring	4 gpm	77		132	45	419	7.4	107		142		496	310			.5 H_2S				Bottled for drinking.
4	Santa Ysabel Spring	4 mi SE of Paso Robles	220,000 gpd	94		28	46	350	8.1	29		361		188	173			31 H_2S				Still flowing in 1979. Fe: 8.1 ppm Al: 6.6 ppm
5	Iron Spring	200 yds NW of Mud Baths	1 gpm	64		45	66	313	trace	15		308		241	224							Fe: 12 ppm Trace H_2S
2	Lithium Spring	30 yds W of Mud Baths	8 gpm	122																		
	Name of Well				Total Depth																	
6	Grand Central "Spring"	NW of 10th and Park Street	"strong"	hot	510 ft.																	Drilled 1911, used for spa. Abandoned about 1925
7	Main Sulphur Spring	W of 11th and Spring Street	2,000,000 gpd	107.6	640 ft	38	16	331	20	66		350		206	31			52 H_2S				Used for Hotel and spa.
8	Municipal Baths	SW of 11th and Pine Street	380,000 gpd	108.6	392 ft	38	16	331	20	66	726	350		206	31		Trace	52 H_2S			1517	Large public spa.
9	R.C. Heaton Well	NE of 13th and Park Street	est. 500,000 gpd	106	230 ft	22.4	18.1	432.6			890.6	0		238	4.3	0		H_2S Odor	7.4	1739	1164	Drilled about 1905. Once used in a bath house.
10	Lithium "Spring"	30 yds W of Mud Bath	small	118	140 ft.																	Used for drinking.

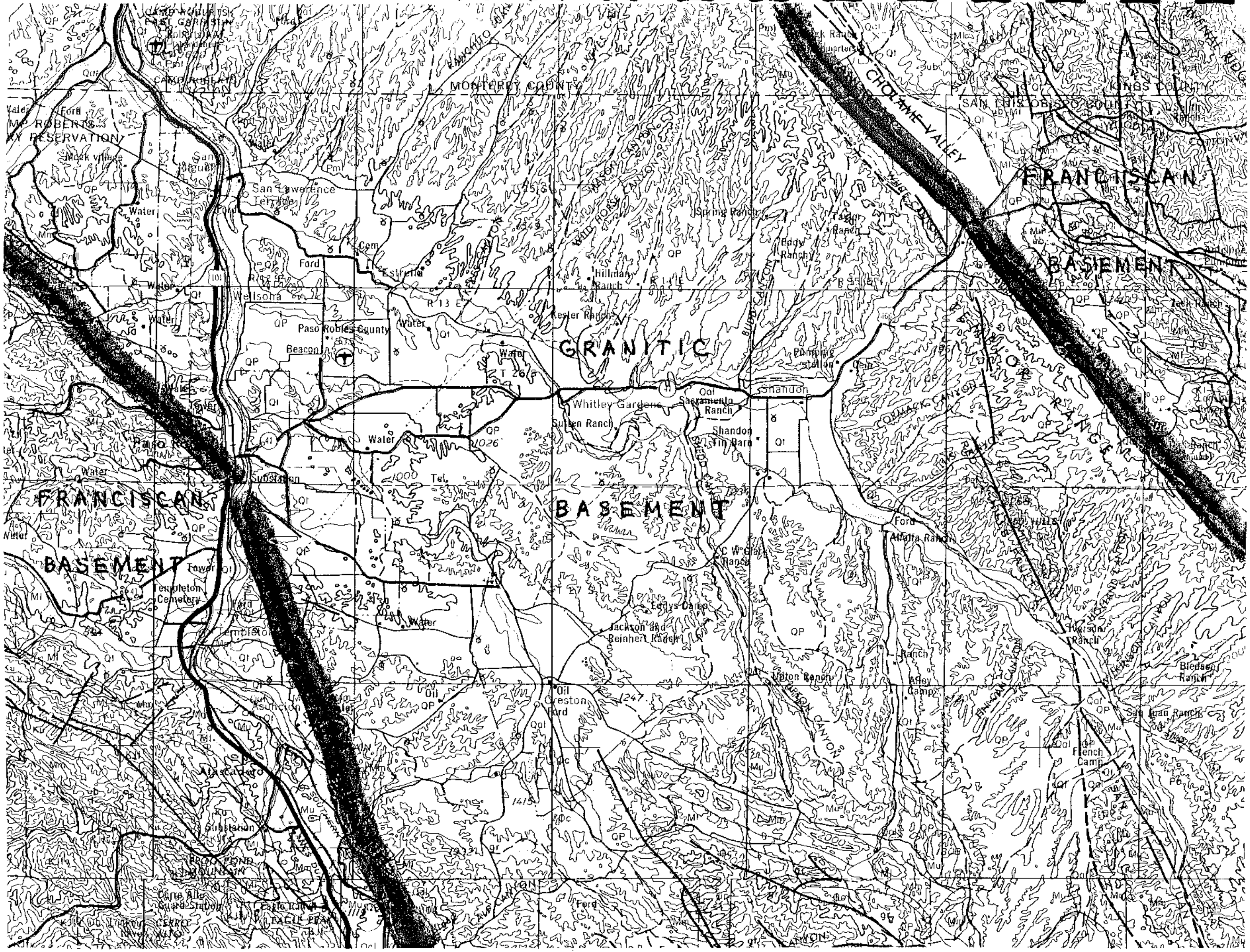


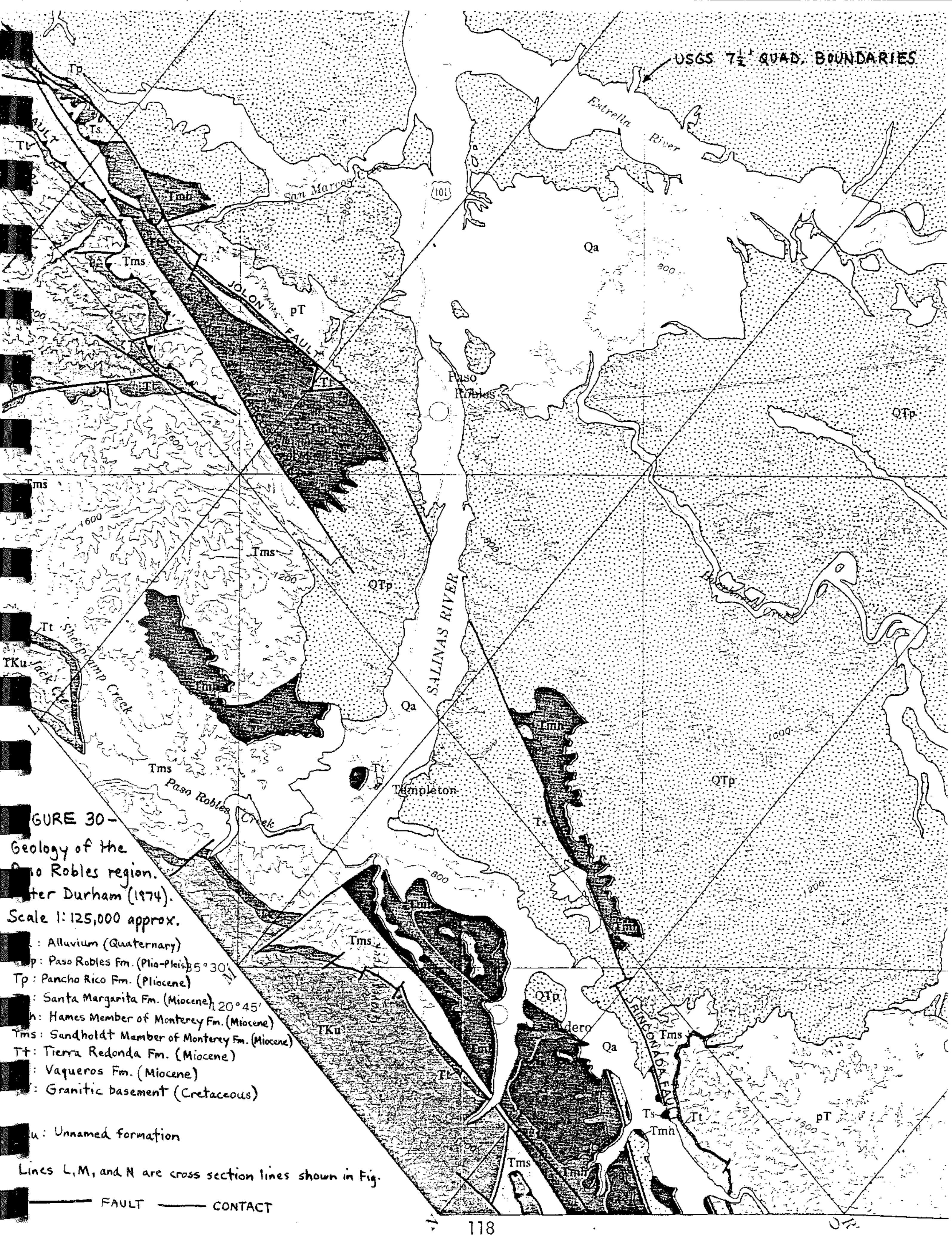
FIGURE 29 — Distribution of basement rock in Paso Robles region. Base map is Calif. Div. Mines and Geology Geologic Atlas, San Luis Obispo Sheet, 1958, scale 1:250,000.

vicinity of the geothermal resource: one large outcrop 18 km to the southeast of Paso Robles (the La Panza High) and a smaller exposure 5 km to the northwest (Figure 30). Durham (1974) calls the smaller exposure a possible outlying part of the La Panza High. Gravity and magnetic data indicate that granite exposure northwest of town extends 3 km under Paso Robles to about the location of an inferred fault through the natural hot springs (Dibblee, 1976). The remainder of the resource is apparently north of the La Panza High, in a depression in the basement possibly formed by folding and/or faulting.

Sediments atop the basement in the Paso Robles area consist mostly of marine arkosic sandstone, organic shale, and mudstone. These strata range in age from lower Miocene to Pliocene, and are coarser than stratigraphically-equivalent beds at greater distances from basement (Durham, 1974).

The Vaqueros Sandstone of early Miocene age overlies the granitic basement throughout much of the area and is the oldest sedimentary formation in the region. This formation, of marine origin, attains thicknesses of up to 450 meters but does not crop out in the geothermal resource area. The lithology of the Vaqueros consists of sandstone with some mudstone and conglomerate. Calcite cementing is common.

The Miocene Monterey Formation is the most widespread marine unit in the region. The formation consists of two members in the Paso Robles area: the Sandholdt (lower) and the Hames member. Where completely penetrated by wells in the study area, the formation is up to 750 meters thick. The Sandholdt Member is up to 450 meters in thickness in the resource area and is composed of calcareous mudstone, shale, and some chert. Stratigraphically above the Sandholdt is the Hames member, which



GURE 30-
Geology of the
o Robles region.
ter Durham (1974).
Scale 1:125,000 approx.

Lines L, M, and N are cross section lines shown in Fig.

consists of fine-grained porcelaneous rocks, siliceous mudstone, chert, and rare sands. The Hames exhibits variable color, bedding, and coarseness. Tuff, olivine basalt, diabase, and bentonitic clay in the Monterey indicate volcanic activity in the Southern Salinas Valley during the Miocene.

The Tierra Redonda Formation is a sandy rock unit equivalent to the finer portions of the Sandholdt (lower) member of the Monterey Formation. Not common in the Paso Robles resource area, this Miocene formation overlies the Vaqueros and, in places the basement, and is easily confused with the Sandholt.

A sandy formation known as the Santa Margarita Formation is the stratigraphic equivalent of the Hames member of the Monterey Formation, but is coarser textured and lenticular in character. It intertongues with or overlies the Hames and lies beneath the Paso Robles Formation. The unit varies in thickness from zero to over 600 meters in the area, and is not present in the western and southern parts of the area. Medium- to coarse-grained light-colored sandstone in massive beds characterize the Santa Margarita Formation, which contains late Miocene fossils of shallow marine origin. This formation appears to be the source of hot water from wells in some cases.

The Paso Robles Formation of Plio-Pleistocene age consists of contintental sediments that accumulated after the retreat of the Tertiary sea, an event associated with Late Pliocene diastrophism that uplifted the Coast Ranges by folding and thrusting. Sub-aerial deposition as stream and lake deposits has left widespread outcrops that consist of sandstone and conglomerate with some mudstone and limestone. Bedded gypsum and lignite are also present in places. Depositional features include crude bedding, poor sorting, channel structures and crossbedding, all of which are typical of non-marine, fluviatile deposition in valleys and basins of the recently folded Late-Pliocene landscape. Calcareous induration is common, but the friable, easily weathered nature of the formation prevents development of resistant outcrops and one must look at road cuts and stream banks for exposures. The discontinuous nature of members in this formation accounts for the difficulty in correlating beds over any distance. The source rocks for the Paso Robles Formation consisted of the uplifted marine Miocene formations, such as the Monterey and Santa Margarita, as well as debris from the nearby Franciscan or granitic basement (Taliaferro, 1943). Fossils are rare.

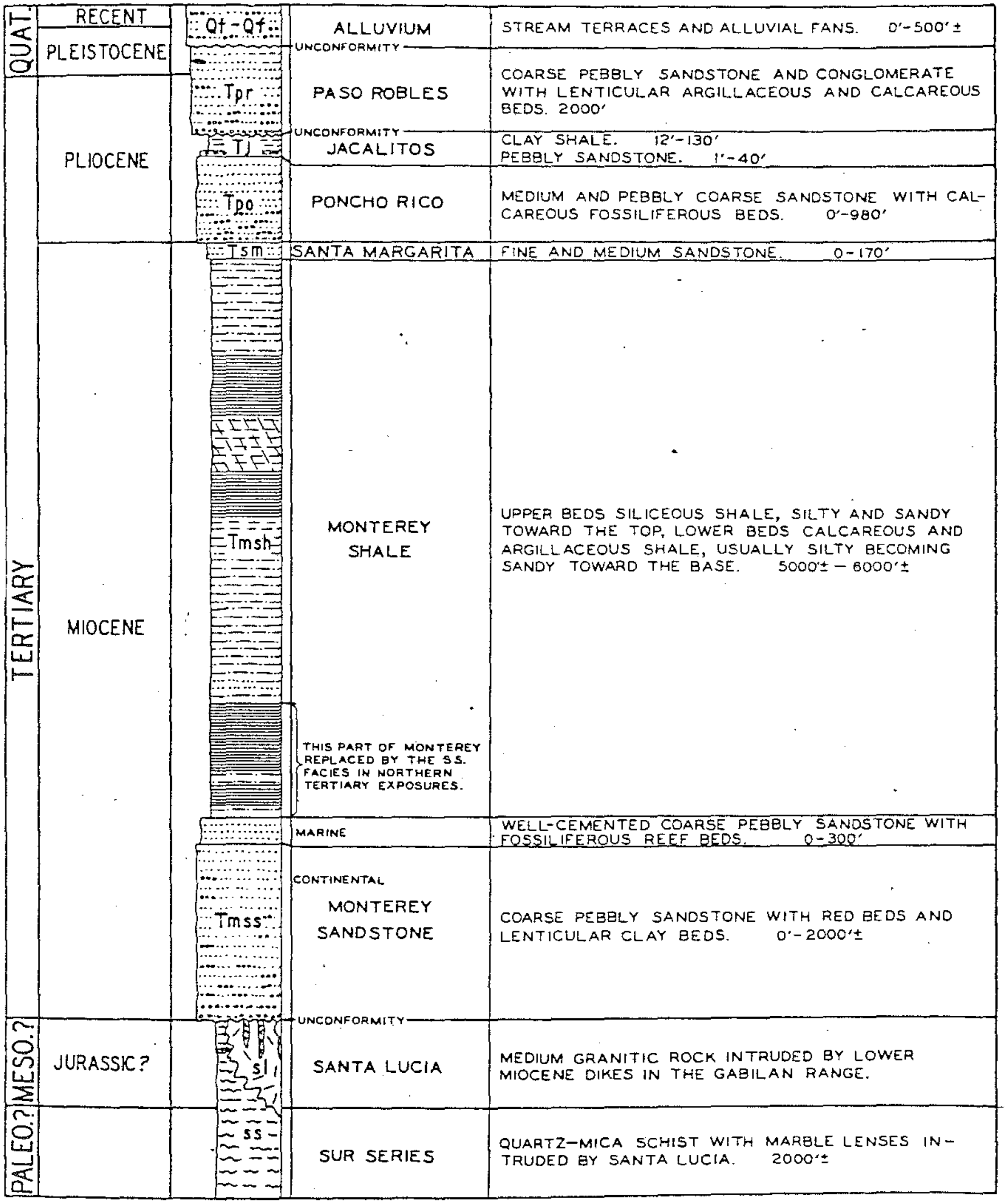
The Paso Robles Formation is of great interest in the study of low-temperature geothermal resources for it is reported to be the main water-bearing unit in the region. It contains clastic sediments of almost all sizes. Conglomerate beds are found up to tens of feet thick showing channels, crossbedding and discontinuous lateral extent; the strata range from friable and porous to dense and cemented. Exposures of the conglomerate are usually very light in color, due largely to the siliceous Monterey pebbles present. Sandstone members may be coarse to fine in texture, poorly sorted, and often contain pebbles of the Monterey. The strata range from massive to poorly bedded and contain the same depositional structures as those found in the conglomerate. Some siltstone and mudstone are present; surface exposures are very-light-colored gray or pale orange. Limestone occurs as rare, thin beds up to 1.5 meters thick, which exhibit a weathered appearance similar in color to the siltstones (Durham, 1974).

The Paso Robles Formation is up to 600 meters thick in the study area, but the upper portions have been lost to erosion nearly everywhere. Pleistocene activity on the Rinconada fault has folded and faulted the Paso Robles in some places, but the incompetent nature of the formation has obscured the resulting structure. Topographic lineaments and the alignment of springs may indicate faults in the formation (DWR, 1958).

In the region of the geothermal resource, the Paso Robles Formation overlies the Santa Margarita or older rocks, such as the Monterey or granite basement. The contact with the Santa Margarita must be conformable, but all other contacts are unconformable.

The only material in the region younger than the Paso Robles is Quaternary alluvium, which consists of unconsolidated gravel, sand and silt. It closely resembles the Paso Robles Formation except that it shows no apparent structural deformation. Found mainly in present river valleys, the alluvium is poorly sorted, massive to crudely bedded, and contains channel structures and cross-stratification. Originating along the upper portions of the present-day streams, it is usually less than 9 meters thick but occurs in thicknesses of up to 40 meters near the Salinas River.

The structure of the area is dominated by the Rinconada Fault, which trends northwest through the town of Paso Robles (Figures 29, 30 and 31) and forms the southwestern border of the Salinan Block. The fault is probably obscured by alluvium near the Salinas River (Durham, 1974). The fault was active in the Late Cretaceous or Early Tertiary, during crustal shortening perpendicular to the continental margin, and again in the Late Tertiary and Pleistocene when right-lateral displacement occurred (Durham, 1965; Dibblee, 1976). This activity produced offset and deformation in the lower Paso Robles Formation as well as in the



QUAT.	RECENT	Qt-Qf	ALLUVIUM	STREAM TERRACES AND ALLUVIAL FANS. 0'-500'±
			UNCONFORMITY	
QUAT.	PLEISTOCENE	Tpr	PASO ROBLES	COARSE PEBBLY SANDSTONE AND CONGLOMERATE WITH LENTICULAR ARGILLACEOUS AND CALCAREOUS BEDS. 2000'
			UNCONFORMITY	
TERTIARY	PLIOCENE	Tj	JACALITOS	CLAY SHALE. 12'-130' PEBBLY SANDSTONE. 1'-40'
TERTIARY	PLIOCENE	Tpo	PONCHO RICO	MEDIUM AND PEBBLY COARSE SANDSTONE WITH CALCAREOUS FOSSILIFEROUS BEDS. 0'-980'
TERTIARY	MIOCENE	Tsm	SANTA MARGARITA	FINE AND MEDIUM SANDSTONE. 0-170'
TERTIARY	MIOCENE	Tmsh	MONTEREY SHALE THIS PART OF MONTEREY REPLACED BY THE S.S. FACIES IN NORTHERN TERTIARY EXPOSURES.	UPPER BEDS SILICEOUS SHALE, SILTY AND SANDY TOWARD THE TOP, LOWER BEDS CALCAREOUS AND ARGILLACEOUS SHALE, USUALLY SILTY BECOMING SANDY TOWARD THE BASE. 5000'± — 6000'±
TERTIARY	MIOCENE	Tmss	MARINE	WELL-CEMENTED COARSE PEBBLY SANDSTONE WITH FOSSILIFEROUS REEF BEDS. 0-300'
TERTIARY	MIOCENE	Tmss	CONTINENTAL MONTEREY SANDSTONE	COARSE PEBBLY SANDSTONE WITH RED BEDS AND LENTICULAR CLAY BEDS. 0'-2000'±
			UNCONFORMITY	
MESO.?	JURASSIC?	sl	SANTA LUCIA	MEDIUM GRANITIC ROCK INTRUDED BY LOWER MIOCENE DIKES IN THE GABILAN RANGE.
PALEO.?		ss	SUR SERIES	QUARTZ-MICA SCHIST WITH MARBLE LENSES INTRUDED BY SANTA LUCIA. 2000'±

FIGURE 31 — Composite columnar section of Paso Robles area.

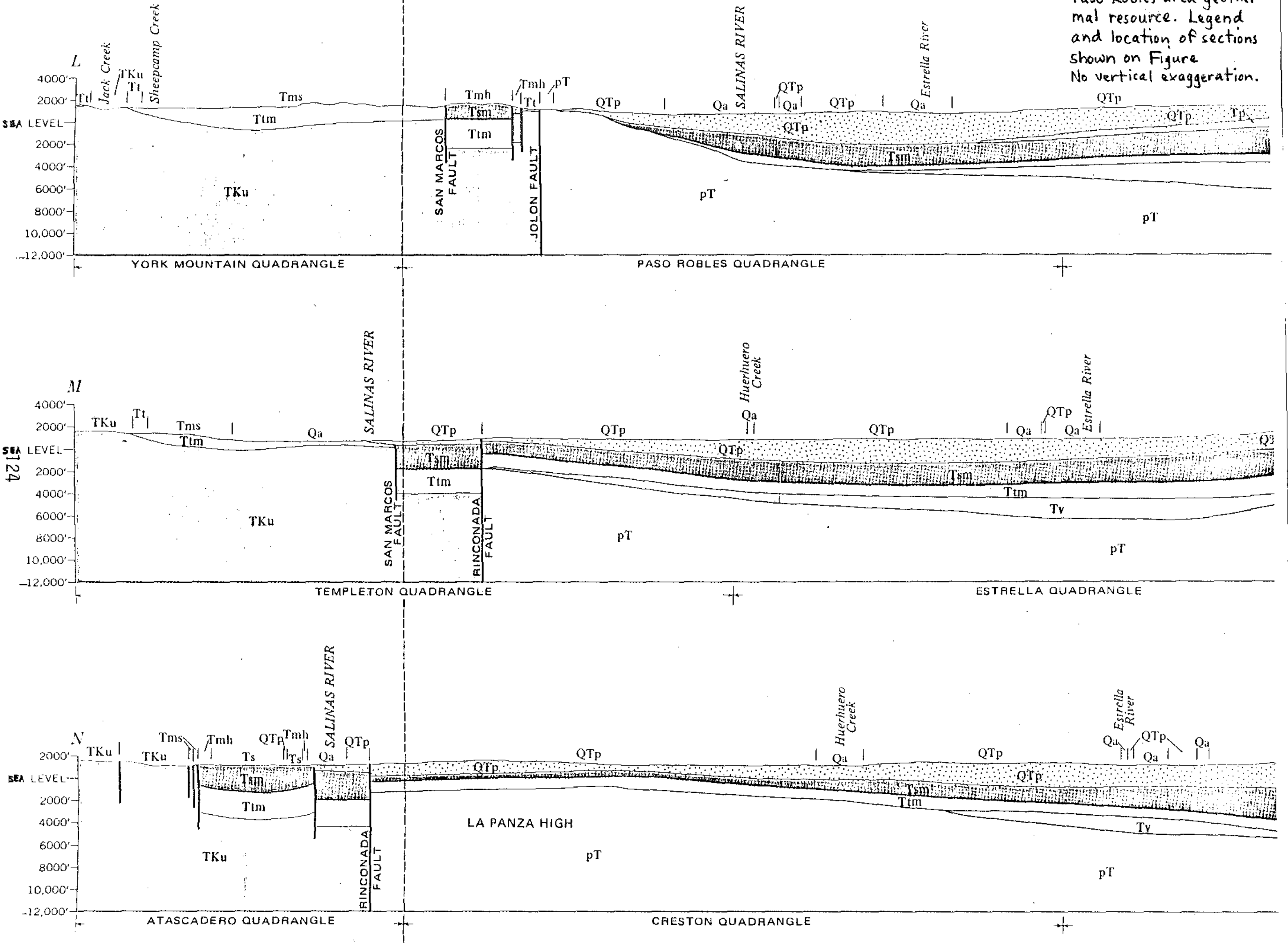
older Miocene and Pliocene units (Dibblee, 1976). Zones of folding, subparallel to the Rinconada fault, are found in the Monterey and Paso Robles Formation. These zones occur in the southwestern, western, and northwestern portions of the geothermal resource area. Published cross sections of the area are shown in Figure 32, but do not include sufficient detail to show the above-reported folding.

GEOHYDROLOGY AND CHEMISTRY

The supply of water to the Coast Ranges and, in particular, to the Paso Robles area is derived directly from precipitation with some additional input from groundwater flow. Aquifers that occur beneath the rolling hills, terraces, and river beds, appear to be recharged by percolation into natural channels, with deep aquifers receiving water by deep penetration or by direct recharge in upland outcrops. The percolation of some stream run-off during storms may also be a source of groundwater recharge (Gribi and Thorup, 1963). The mountainous terrain, which consists of consolidated older rocks, is not considered to be water-producing, although granite will yield some water from fractures.

Abundant groundwater and the advent of the deep-well turbine pump in the early part of the century gave rise to irrigated agriculture and the proliferation of water wells. In the Paso Robles area, most water wells produce from the Paso Robles Formation with the exception of some city and private wells in the Salinas River bed, which produce from the alluvium. All prolific producers (some up to several thousand per day) pump from the Paso Robles Formation. Artesian wells also produce from the sands and gravels of this formation. Most warm or hot wells derive

[illegible]RE [illegible] — [illegible]gic [illegible]ions [illegible]gh Paso Robles area geothermal resource. Legend and location of sections shown on Figure
No vertical exaggeration.



their water from the Paso Robles, although faults possibly allow this water to travel from deeper formations. The large volume of water production and potential production derives from the great thickness of the Paso Robles Formation in the area, which is over 600 meters thick in places.

Folding and faulting in the Paso Robles has affected the location and movement of ground water. In some areas, notably near the Rinconada Fault, the formation has been exposed by folding and subsequent erosion. This allows recharge into the sand and gravel members, which, in turn, are the source of water in wells at other locations. In addition, confining clay layers appear to allow artesian pressure to build up, but their lenticular nature can permit localized upward movement of ground water (DWR, 1958) in some topographically low areas. In non-flowing wells, observed standing water levels range from the surface to about 65 meters depth (Bader, 1969). Most ground water in the region of the Paso Robles geothermal resource seems to be unconfined, but flowing wells are found in many parts of the resource. Most flowing wells, both past and present, are hot.

The direction of ground water flow within the Paso Robles Formation is presumed to be toward and subparallel to surface drainage (Bader, 1969). This is supported by a ground water elevation map published by the California Department of Water Resources (DWR, 1958), shown in Figure 33. Complex and poorly understood movement also occurs due to the lenticular nature of the gravels and clays and to the above-mentioned structure.

According to Department of Water Resources reports (1958, 1971, 1978) and local residents, water levels and some artesian pressures have dropped

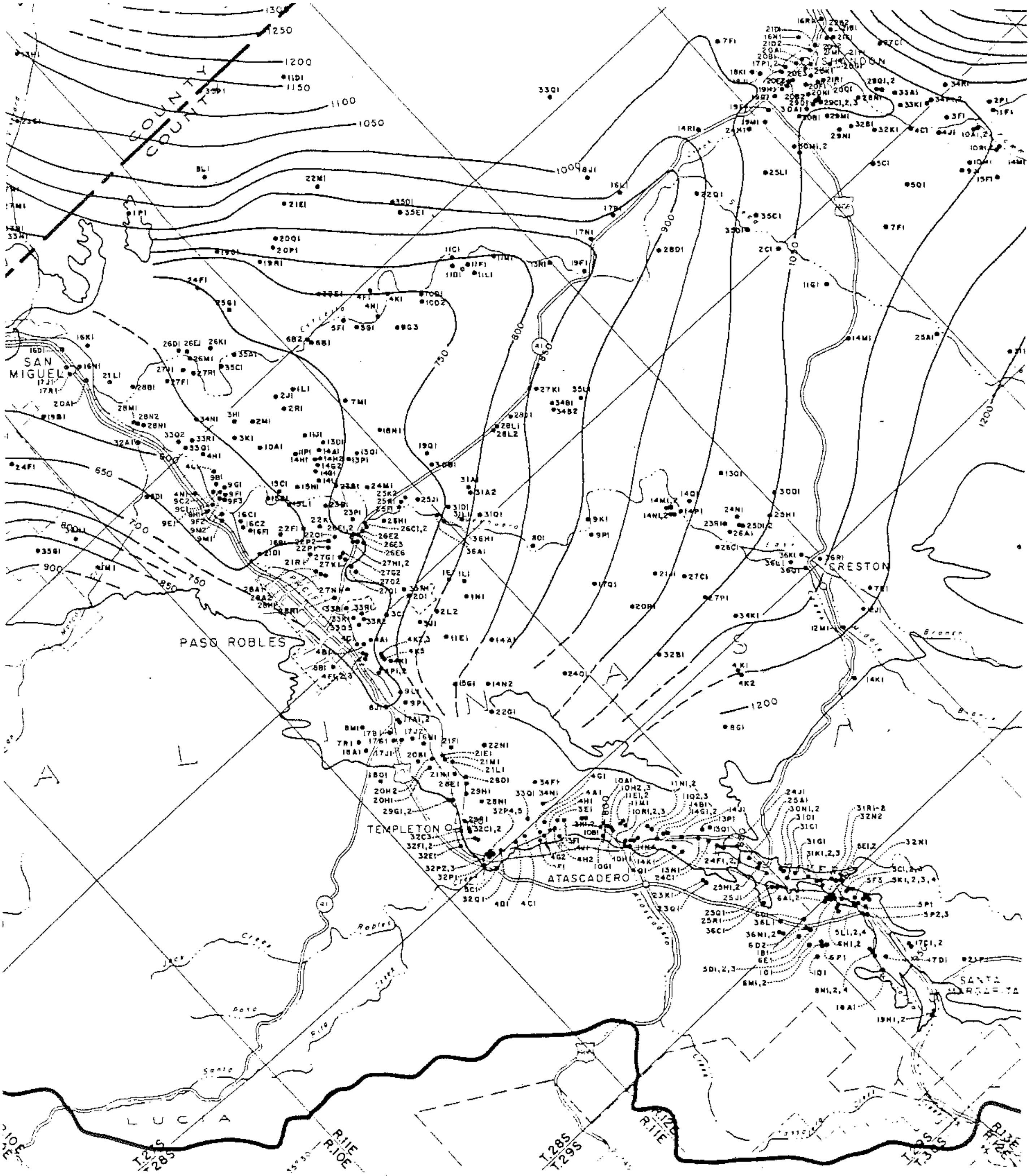


FIGURE 33 — Lines of equal elevation (feet above mean sea level) of ground water in Fall, 1954. Dots represent locations of wells. After Calif. Dept. Water Resources (1958).

over the years. Average values from agricultural wells have shown the Paso Robles aquifers to have the following characteristics: permeability is from 4,130 to 44,570 liters per day per square meter with an average of 8,200, average production per well is 1,900 liters per minute, and specific capacity is about 49 liters per meter of drawdown (DWR, 1958).

The hot water resource in the Paso Robles region exhibits the same hydrologic characteristics as the ground water in general, but differs in distribution and chemistry. Early springs in the town of Paso Robles were used for spas because of the ideal temperature of over 38°C and steady productivity. Wells drilled in the same area reportedly flowed up to 7,600,000 liters per day from relatively shallow depths (195 meters or less). Table 17 lists early springs and wells, while Table 18 gives additional hot wells drilled since about 1940.

Hot water wells and springs appear to produce mainly from the Paso Robles Formation and probably owe their productivity to nearby faults. Most workers in the area believe that faults restrict or control ground water movement at depth (DWR, 1971). The springs and wells in downtown Paso Robles, for example, are not far from the Rinconada Fault and may be along a proposed short fault that extends northward from the Rinconada at the south end of town (Dibblee, 1976). The artesian pressure in these wells may be supplied by recharge in the hills to the west of town, where wells have produced water from the Monterey shale. This inferred fault may provide a conduit for artesian warm water at depth to reach the surface via the springs and shallow wells in the downtown area.

As Figure 34 shows, hot water is also found southeast of Paso Robles. At these locations, the resource is at depths of from 210 to 300 meters in the Paso Robles Formation. Artesian pressure is also found in parts of this region; the hot water is evidently confined by layers

Table 18, SELECTED RECENT WELLS AND THEIR CHEMISTRY

Map No.	Name of Well	Location	Approx. Flow	Temp °F	μmho/cmx 10^6 @ 25°C Elec. Cond.	TDS	pH	Total Depth	Ca ppm	Mg ppm	Na ppm	K ppm	Si ppm	HCO_3 ppm	F ppm	total hardness $CaCO_3$ ppm	Cl ppm	SO_4 ppm	NO_3 ppm	B ppm	Odor	Remarks
11	Borcherdt #5	S. River Rd. at Charolais Rd.		81	1150	805	7.7	400 ft.	21	6.9	275	4.2		210	.8	112	100	92	9	1.2		
12	Butterfield Well	1 mi SW of Airport		83	756	525	7.5	1000 ft.	29	14	149	2		210		130	56	84	7	1.6		Drilled 1966.
13	Creston Park #7	Nr. Creston Rd. 4000'E of River		cold	824	479	7.5	400 ft.	39	22	104			360	0	188	74	15.4	42.2			Abandoned due to sulphur.
14	Sherwood #6	Nr. cor. Creston Rd & Sherwood Rd.		cold	950	650	8.5	~750 ft.	17	6	119	3.1		360		60	77	64	7	1.5	None	
15	Sherwood #9	Nr. cor. Creston Rd. & Scott St.		cold	700	438	7.8	600 ft.	50	16	69	2.3		240		191	61	31	17	.25		
16	Sherwood #11	2000'NE of Well #9		cold				600 ft.												2.3		
17	Thunderbird Well	2 mi S of Paso Robles nr. River		cold	750	500	8.5	210 ft.	104	32.8	39.6	1.7	28	204	.4	400	60.4	74	2	.1	none	Probably produces from alluvium.
18	Bianchi Well	.15 mi NW of Hwy 46 and Freeway	~5 gpm	cold	1890	1180	8.2		7.5	.1	430	8.2			2.4	19	163	209	0	1.2	sulphur	Flow from concrete tub.
19	Cal-Aqua Well	NW/4 14-T27S-R13E	no flow	115	850	555	8.1	1000 ft.	8	1.5	182	1.9		255	.8	25	60	135	5.2	1.3	sulphur	
20	Cal Trans Well	S of Treatment Plant ~500 ft.	50-100 gpm	105	1840	1160	8.4		4.8	0	420	7			2.6	12	153	219	2.4	1.2		
21	Fairgrounds Well	NE of Racetrack @ Fairgrounds	6 gpm	79	1820	1160	8.2		5.5	1.2	430	5.6			2.6	18	180	211	3.0	1.1		Flowing in 1978.
22	Franklin Well	SE/4 of 11-T27S-R12E	5000 gpm	98±	950	650	8.2	3458 ft.	5.4	1.2	256	2.6	8	485	1.2	30	180	70	3	1.5	H_2S Odor	
23	Kleck Well	1 mi NE of Hwy 46 and Freeway	~30 gpm	90	2140	1350	8.3	300 ft.	5.5	0	500	5.8			2.6	14	250		3.0	1.2		Drilled about 1915.
24	Pioneer Museum Well	SE of 21st and Riverside	none	82	1740	1050	8.8		8.3	3.5	400	8.1			2.2	35	168	165	2.4	1.2	sulphur	Shut in
25	Treatment Plant Well	On city sewer treatment property	50-100 gpm	97	1840	1150	8.3		34	18	370				2.2	159	177	229	0	1.2	sulphur odor	Flowing.

Variations in chemistry exist over time and different workers arrive at different values due to sampling and lab techniques.

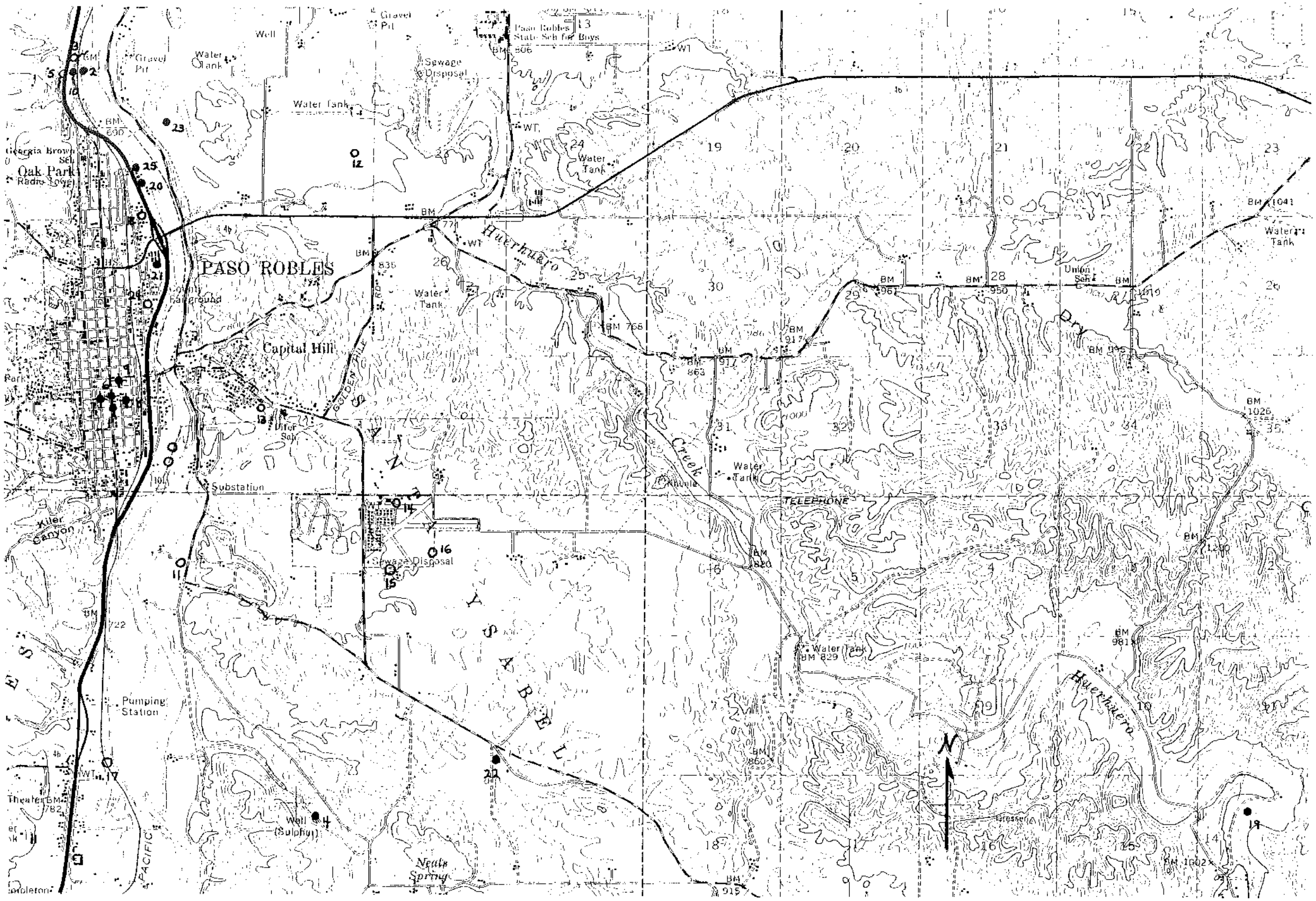


FIGURE 34 — Paso Robles area wells and springs. Numbers refer to data on the wells and springs listed in Table Base map is USGS Paso Robles 15 Min. Quadrangle (1961).

of "blue clay", according to local drillers. Temperatures of up to about $46^{0}C$ are found in the wells southeast of Paso Robles, similar in temperature to the water found beneath the town.

GEOCHEMISTRY

The hot water resource of the Paso Robles area is distinguishable from the local cold ground water not only by its temperature, but also by its chemistry. The hot water is characterized by conspicuous H_2S content. Aeration, which can be accomplished merely by the downhill flow, appears to be a sufficient treatment to dissipate the gas. At Paso Robles, the H_2S was part of the attraction of the early springs and spas for its health-giving properties, but now, its presence has caused the abandonment of many wells by order of the Regional Water Quality Control Board. Water from these unused flowing wells was finding its way into the sewage treatment facility and was ultimately contaminating the Salinas River. Another distinguishing characteristic of the hot-water resource of the Paso Robles area is the salinity of the water. Tables 17 and 18 show Na and Cl concentrations in the geothermal waters. The Franklin well, for example, is a deep (producing interval at about 250 meters) flowing well of elevated temperature and salinity. The high salinity is not found in shallower, cold water wells in the area. The hot wells of downtown Paso Robles likewise have higher concentrations of Na and Cl than nearby cold wells.

The California Department of Water Resources (1971) grouped the Paso Robles springs with other waters of "poor quality", citing high concentrations of fluoride, boron, sodium, and chloride, as well as high total-dissolved-solids content. Cold ground water from the region tends to have a much lower solids content and no associated H_2S gas (Table 18).

The chemical characteristics of the early springs and wells have been studied since the 1800's (Table 17). In addition, some of the more recent wells have also been tested (Table 18).

POTENTIAL USES

The early uses of the Paso Robles geothermal resource have already been discussed. They consisted of spas and mud baths, using hot water derived from springs and shallow wells. But these uses were recreational or medicinal in nature. Today, in this country, we have a rapid consumption of energy, and the hot water that was once used for spas can be used as a direct heat source to reduce our consumption of imported fossil fuels.

At present, small amounts of the natural hot water are still used for bathing, for example, the water produced from the Kleck and Franklin wells. The use is negligible from the standpoint of energy consumption, however, and there are other potential uses to consider. Calaqua, Inc., a firm in the area, is entering the agribusiness sector with a plan to raise channel catfish using the hot water resource. This aquaculture ranch, about 17 km southeast of Paso Robles, may ultimately derive over 95% of its energy requirements from the hot water. This savings is due to the large amount of warm water needed for the farm, which would otherwise have to be heated using conventional sources of energy. The 46°C water from the Calaqua well, after use for the catfish production, will be used for shellfish culture and finally irrigation of crops. The water will also be used for space heating of the facilities. The Calaqua operation is still being developed and its ultimate success remains to be seen.

In addition to aquaculture, the resource could be used directly for space and water heating, especially in the downtown area. This can be expanded to include additional applications for agriculture: heating greenhouses, chicken coops, and barns. Space heating could rely on the hot water resource at Paso Robles, and greatly reduce the consumption of oil and natural gas for this purpose.

Another possible major direct use of hot water is known as process heat. This term is often applied to food processing techniques such as dehydration or sterilization. Other types of process heat applications are water supply treatment, sewage, and solid waste treatment, livestock feed production, refrigeration, and lumber processing and curing. In the long run, many of these uses could be made of the geothermal resource of Paso Robles.

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LOW- AND MODERATE-TEMPERATURE GEOTHERMAL RESOURCES OF THE BRIDGEPORT-WESTERN BODIE HILLS REGION, CALIFORNIA

INTRODUCTION

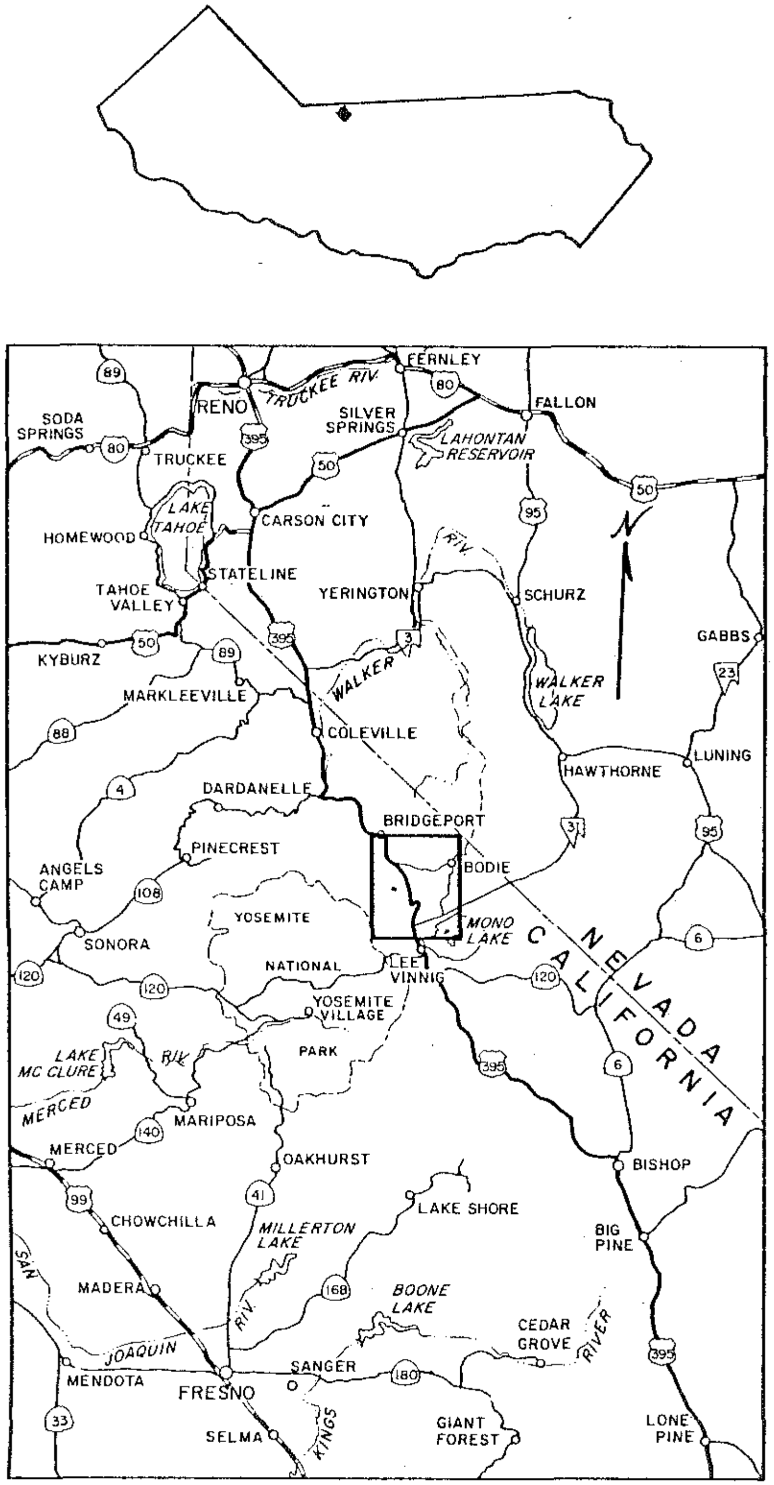
This report presents data gathered during a reconnaissance study of the geology and geothermal resources of the Bridgeport-western Bodie Hills region of California. It is the first portion of a detailed study of the area, financed by a grant to the Division of Mines and Geology from the U.S. Department of Energy to assess low- and moderate-temperature geothermal resources throughout California.

The town of Bridgeport and the western part of the Bodie Hills are some 100 kilometers southeast of Lake Tahoe, near the Nevada border in T 4 and 5N, R 25 and 26E, MDB&M (Figure 35). They are on the east side of the triangular-shaped, flat floored Bridgeport Valley, which has an elevation of about 1,975 meters at Bridgeport. Mountains that surround the valley include the Sierra Nevada on the west and south, the Bodie Hills on the east, and the Sweetwater Range on the north. Each group of mountains has peaks that exceed 3,000 meters in elevation.

The climate of the Bodie Hills and Bridgeport Valley is semi-arid. The following climatological data were taken from Al-Rawi (1969):

Station	Elevation (meters)	Annual Precip. (mm)	Precip. May-Sept. (mm)	Mean Annual Temp. (°c)	Yrs. of Precip.	Records Temp.
Bodie	2551	241.6	113.8	3.7	5	5
Bridgeport	1972	202.9	47.0	5.2	19	11

Most of the precipitation at Bridgeport falls during the winter months as snow; some rain falls during summer thunderstorms. The same is true of Bodie, except that a higher proportion of its precipitation falls



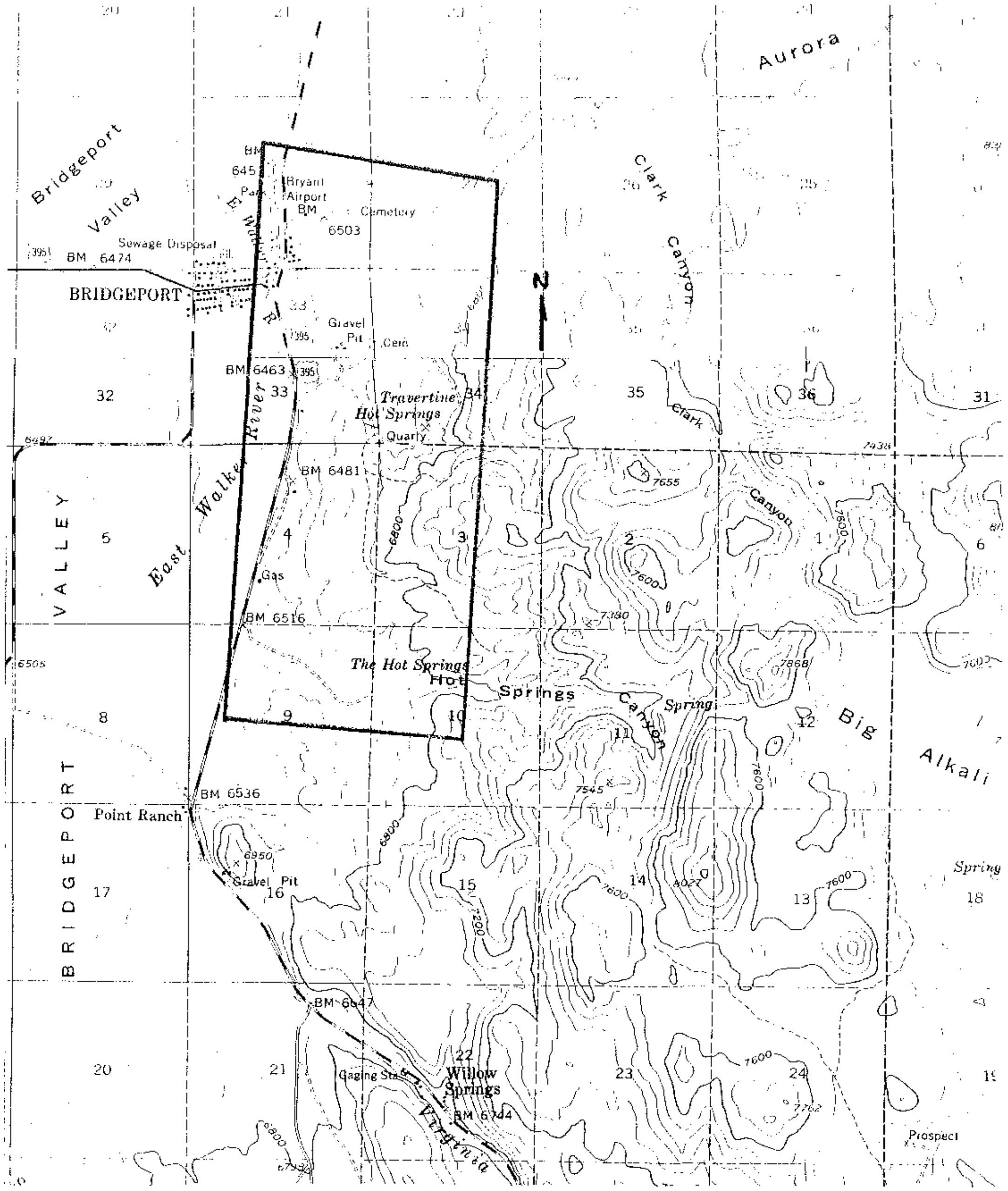


FIGURE 35 – Location of the Bridgeport – Bodie Hills area, California. Area outlined in red above is approximate area of detailed geological and/or geophysical work performed by CDMG in 1977-78. Base map is USGS Bodie and Bridgeport 15 Min. Quadrangles.

during summer thunderstorms. Freezing temperatures are common even during the summer months.

Vegetation is typical of the Great Basin country with sagebrush types predominant. Scattered juniper and piñon pine are found at the higher elevations east of Bridgeport. The floor of Bridgeport Valley is treeless and covered by grasses.

Because of the area's remoteness, it did not receive much geological study until the late 1960's. To date, the most detailed studies of Bridgeport Valley and the Bodie Hills include those by Chesterman (1968), Al-Rawi (1969), Chesterman and Gray (1975), Kleinhampl and others (1975), and Zeller (1977).

The present study focuses mainly on the geothermal resources of an area just east and southeast of Bridgeport with some emphasis on pertinent parts of the western Bodie Hills (Figure 35). The study included about a week and a half of geologic field reconnaissance during the autumn of both 1977 and 1978 plus a detailed literature search and interpretation of conventional black and white aerial photographs of various scales.

Previous Study of the Area's Geothermal Resources

Little study or exploration of the geothermal resources of the Bridgeport-western Bodies Hills area has been conducted. One reason is the meager surface evidence of a high-temperature resource at depth, a resource that is capable of generating electricity. Another is the sparse population and low economic base of the region. Only the very recent interest in uses of the low-temperature waters has spurred study of this area.

In 1962, Magma Power Company drilled an exploratory geothermal well at The Hot Springs. Some publications reported the well to be at Travertine Hot Springs, but E. Zajac, drilling supervisor of the well, confirmed that it was at The Hot Springs. Thus, no exploratory drilling has been conducted at Travertine Hot Springs, or elsewhere in the area.

Hannah (1975), in her overview of the low-temperature geothermal resources in northern California, discussed the potential of the Bridgeport Valley with emphasis on the local thermal springs. Renner and others (1975) and Brook and others (1979) reported quantitative data and estimates of the volume and heat content of the geothermal reservoir that underlies the western Bodie Hills. Mariner and others (1977) investigated the geochemistry of Travertine Hot Springs and The Hot Springs in order to determine the temperature of the thermal aquifers that supply the springs.

The California Department of Transportation, because of its interest in using geothermal fluids for heating a proposed maintenance station at Bridgeport, prepared an internal report in 1978 that covered much of the same subject matter discussed in the present report. They study was of a reconnaissance nature, and no associated drilling or geophysical work were performed.

STRATIGRAPHY

The stratigraphy of the region consists basically of three main groups of rocks: a basement composed of metamorphic and plutonic rocks of pre-Cenozoic age, which is overlain by Cenozoic volcanic rocks, which in turn are overlain by Quaternary glacial and alluvial deposits. Plate 5 shows the regional distribution of these rocks.

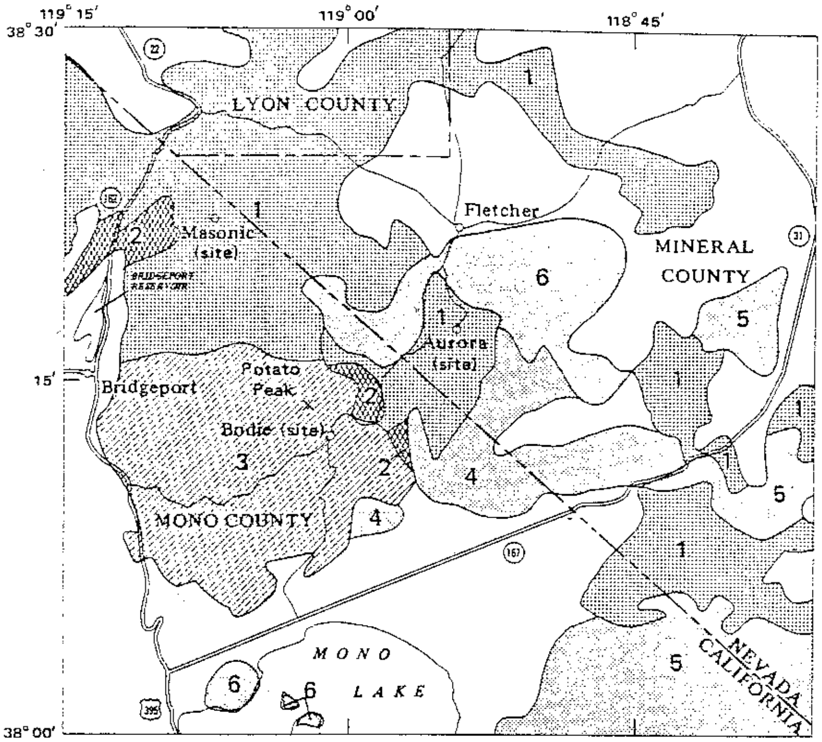
In the immediate area around Bridgeport, only the Cenozoic volcanic rocks and the Quaternary deposits are exposed at the surface. These two groups are discussed more fully below.

Cenozoic Volcanic Rocks

Except for small areas of alluvium in local basins and limited areas of glacial outwash deposits near Bridgeport, the entire western part of the Bodie Hills near Bridgeport is composed of Cenozoic volcanic rocks of intermediate composition. Chesterman (1968) and Chesterman and Gray (1975) classified these rocks as dacite and grouped them as the "Willow Springs Formation". They are part of a widespread distribution of Cenozoic volcanic rocks, shown in Figure 36.

The dacite occurs as massive flows and possibly intrusions and as breccia. The matrix of the breccia is either soft and mud-like or hard and lava-like. Because of the limited area studied, it is not prudent to estimate the relative proportions of massive to brecciated. Al-Rawi (1969) estimated, however, that breccia makes up about 75-80% of the volume of the Cenozoic volcanic rocks in the entire region.

Chesterman (1968), Chesterman and Gray (1975), and Kleinhampl and others (1975) considered the volcanic rocks near Bridgeport to be about 8 to 10 million years old. Al-Rawi (1969) considered them to be at least 12.5 million years old. Al-Rawi also believed them to be the local equivalent of the widespread andesites found in the vicinity of Ebbetts Pass and Lake Tahoe. The table below lists known Potassium-Argon ages for several flows and intrusions in the western part of the Bodie Hills; the locations of the samples are



EXPLANATION

6

Basaltic andesite

Includes some olivine-bearing basalts, several thousand years to about 3 m.y. old. Also includes rhyolites not shown separately, some of which are about 3½ m.y. old

4

Andesitic and dacitic lavas, domes, and minor tuffs

Approximately 2-4 m.y. old

5

Olivine basalt

2½-4½ m.y. old

3

Dacitic and andesitic lavas, and tuff breccias

Approximately 8-13 m.y. old. Also include some younger rhyolites

2

Trachyandesitic welded tuff

9-10 m.y. old

1

Andesite and dacite lavas, intrusive bodies, and breccias with oldest absolute ages known

13.5-15.4 m.y. old at Aurora. Also include numerous rhyolitic flows and associated intrusive bodies and welded tuffs that are separated into older and younger rhyolites on plate 1, consisting of rocks possibly 22-29 m.y. old in southeastern and extreme northwestern part of map, rhyolitic welded tuff 11-12 m.y. old east of Mono Lake, and rhyolites in the vicinity of Aurora with ages of 2.5-11 m.y.

——— Contact

FIGURE 36- Distribution of Cenozoic volcanic rocks in the region. After Kleinhampl and others (1975).

shown on Plate 5. Unfortunately, no age dates were obtained near Bridgeport.

Type	Location	Mineral	Age	Source
Rhyolite plug	NW1/4 sec. 31, T 4N, R 26E	Biotite	5.7 ± 0.2my	Kleinhampl and others (1975)
Rhyodacite plug	sec. 7, T 4N, R 26E	Biotite	5.2 ± 0.3my	Kleinhampl and others (1975)
		Hornblende	5.4 ± 0.6my	Kleinhampl and others (1975)
Dacite flow	Left center, sec. 12, T 4N R 25 E	Biotite	8.0 ± 0.2my	Kleinhampl and others (1975)
Andesite flow	sec. 26, T 4N, R 25E	Plagioclase	7.8 ± 0.2my	Gilbert and others (1968)

Table 19. Age dates of volcanic rocks in the eastern Sierra Nevada province.

Quaternary Sediments

Between Bridgeport and Travertine Hot Springs (Plate 5), the Cenozoic volcanic rocks are overlain unconformably by gently-warped sands and gravels that were deposited as glacial outwash during the Pleistocene. The steep-sided hill just east of town is composed entirely of such material, which is found at a maximum elevation of about 2050 meters. The deposits appear to be at least 75 meters thick.

Outcrops are well-indurated because of case-hardening. In this process, silica-rich solutions migrated through the porous sands and gravels to the ground surface. Evaporation of the solutions at the surface and the resultant precipitation of the silica produced the extremely hard outcrops. The hardest of these can be observed as the bold ledges on the north and west slopes of the hill east of Bridgeport. In contrast, the sediments exposed in fresh cuts, such as at the county quarry 1 km southeast of town, are somewhat friable and weakly consolidated. The quarry also reveals abundant small-scale cross-bedding and cut-and-fill structures in the sediments.

Pebbly sandstones are the most common deposits, although remnants of cobble conglomerate are present in the form of in-place layers and float and indicate high-energy stream environments. The sand-sized particles are typically angular and medium to coarse grained. They include an abundance of quartz and feldspar, lesser amounts of mafic minerals (substantial biotite, which indicates rapid deposition or short transport), and rock fragments. Cobbles and pebbles are rounded, the former generally less than 20 centimeters in maximum dimension, and consist of volcanic, metamorphic, and plutonic rocks.

The angularity and coarseness of the fragments, the cross-bedding, and the cut-and-fill structures all indicate that the sediments were deposited in a high-energy environment probably associated with braided stream channels that originated at the melting snouts of local glaciers. The composition of the debris, because it contains so much granitic and metamorphic material, indicates that the source was probably in the Sierra Nevada to the west and south. Indeed, lateral moraines at the head of Bridgeport Valley trend north-south and the associated streams were responsible for flooding the valley with debris. The present flat floor of Bridgeport Valley is composed of the most-recently deposited debris, whereas the bluffs and terraces between Bridgeport and Travertine Hot Springs are meager eroded remnants of older outwash material.

Distribution of Conglomerate:

There are few remnants of conglomerate in the study area; they were recognized mainly from float debris scattered in places over the ground surface. The areas of debris are marked by the symbol "cg" on a geologic map (Plate 6) of the Travertine Hot Springs area.

The highest exposures of conglomerate are at an elevation of about 2040 meters, one in the northeast corner of section 33 and one in the northwest corner of section 34. The latter is an eroded remnant on a small hill and is about 8 meters in maximum thickness. It may be correlative with the gravels in section 33. Just northeast of these exposures are scattered cobbles at an elevation of about 2025 meters.

Along the southern part of the section line between sections 33 and 34 is an inlier of dacite surrounded by recent alluvium. The northwest half of this inlier is relatively flat and has some scattered metamorphic and igneous cobbles, which indicate that the flat area is probably an old river terrace. The terrace is at an elevation of about 2010 meters.

Southwest of this inlier are two terraces cut into the volcanic bedrock, the smaller at an elevation of about 1980 meters and the other at about 2010 meters. Both are capped with scattered cobbles indicative of former river channels. The upper terrace may be correlative with the terrace on the inlier to the northeast, discussed above. The lower may be correlative with an exposure of scattered cobbles that rest on Quaternary outwash sediment about 300 meters directly to the west.

STRUCTURE

Regional

According to Al-Rawi (1969), structural warping has been much more important than faulting in the evolution of the Bridgeport Valley-Bodie Hills region. This warping, the axis of which is shown in Figure 37, began in late Pliocene - early Pleistocene time and upwarped the Bodie Hills region into a dome and downwarped the Bridgeport Valley into a basin. Because it is not characteristic of Basin and Range tectonics, the warping is evidently a local phenomenon. Al-Rawi (1969) proposed that vertical and lateral movement of subcrustal material, either as molten magma or by plastic flow, caused this pattern of deformation. Vertical movement upwarped the Bodie Hills and may have been associated with lateral withdrawal of material from beneath the adjacent basins, including Bridgeport Valley. This idea is supported by the voluminous amounts of volcanic rock in the Bodie Hills.

The pattern of faults in this region is very regular (Figure 37), which suggests that it has been imposed by the regional pattern of deformation characteristic of the Basin and Range province. Fault trends are either northeast or north-northwest, and motions are predominantly dip-slip, although there is some left-lateral strike-slip motion (Chesterman and Gray, 1975). In general, fault traces on the ground surface are nearly straight or slightly curved, thus the dips are probably steep. Although faulting began in pre-Miocene time (Al-Rawi, 1969) and has continued up to the present, faults in rocks younger than 3 million years are generally small and few in number. Most separations measured by Al-Rawi (1969) are small (<30 meters).

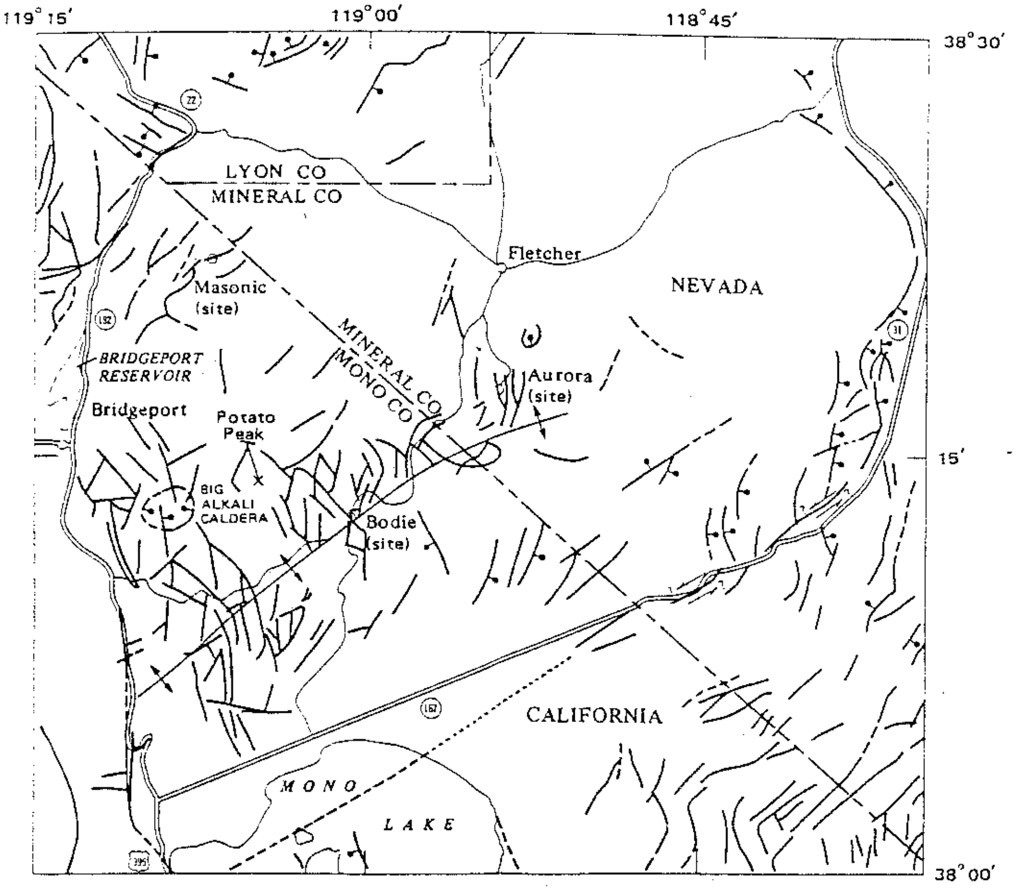


FIGURE 37 – Faults in the area shown in Figure 2. Includes Al-Rawi's (1969) speculated axis of upwarp of the Bodie Hills. After Kleinhampl and others (1975).

EXPLANATION

Fault

Dashed where inferred; dotted where concealed. Bar and ball on downthrown side. Arrows indicate relative horizontal movement

Axis of warp

Two previously unmapped faults along the northwest shore of Bridgeport Reservoir were recognized during examination of aerial photographs of the region (Figure 38). Both faults trend about N35E and cut a Quaternary alluvial fan. The northwest trace is about 1000 meters long, while the southeast trace is at least 2000 meters long and appears to extend even farther under the Bridgeport Reservoir. The sense of movement was not determined.

Local

Because faults probably control the circulation of thermal waters in the study area, their locations and attitudes are important in the search for such waters. Consequently, local faulting is discussed in detail below:

Faults Recognized by Chesterman and Gray (1975):

Chesterman and Gray (1975) show several northeast- and northwest-trending faults in the area just east and southeast of Bridgeport. They also show a fault east of The Hot Springs that trends east-west. These faults are identified by numbers on Figure 39 and are discussed below.

1) Shown as concealed, this fault was interpreted as the structural boundary between the flat part of Bridgeport Valley and the hilly relief to the east. The existence of this fault could not be confirmed by brief field checks conducted during the present study.

2) This northwest-trending fault is shown to pass through Travertine Hot Springs. On the aerial photograph used for both his field mapping and for the compilation of Chesterman and Gray's (1975) map, Chesterman showed an offset of lake beds (glacial outwash

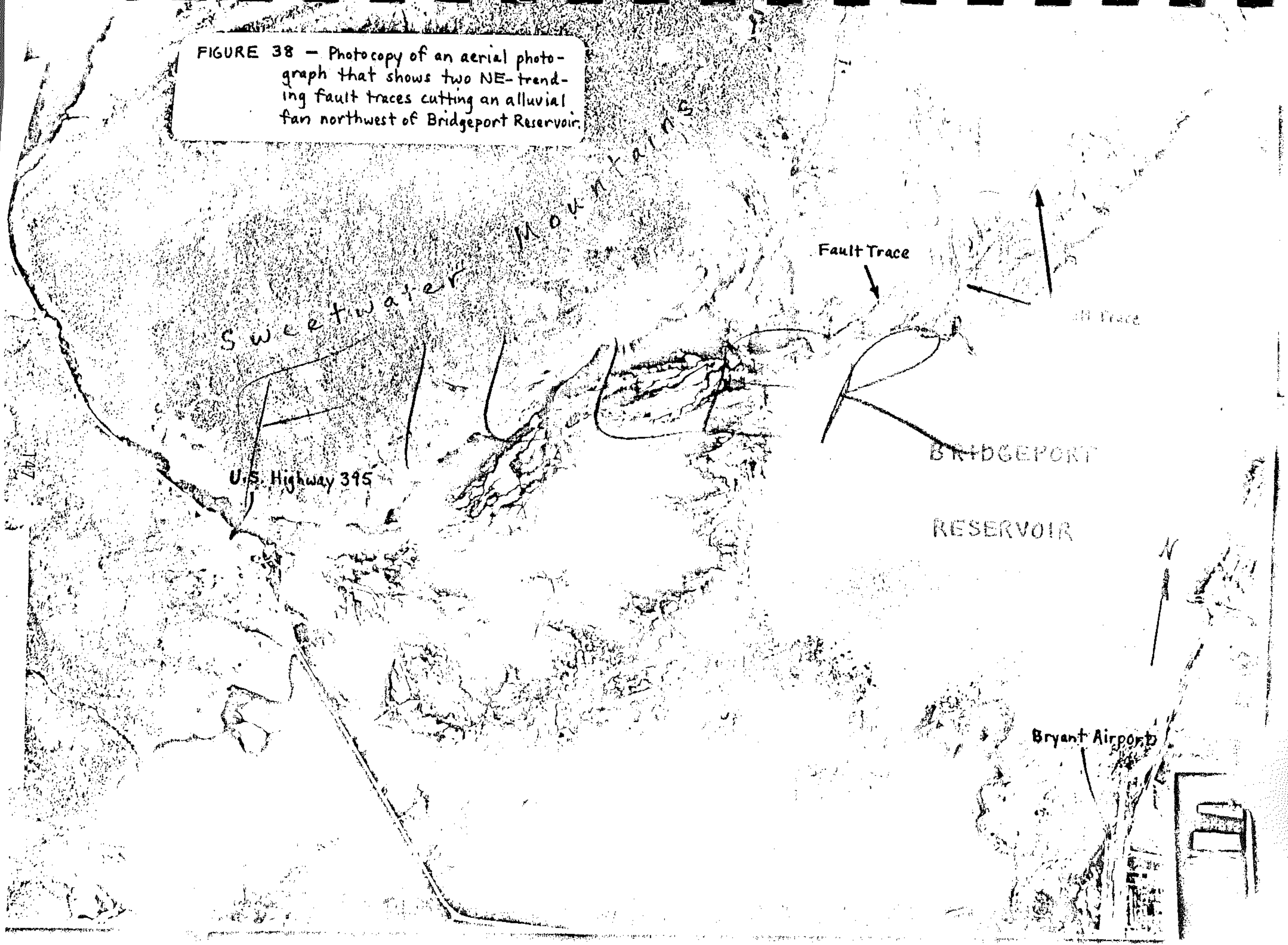


FIGURE 38 — Photocopy of an aerial photograph that shows two NE-trending fault traces cutting an alluvial fan northwest of Bridgeport Reservoir.

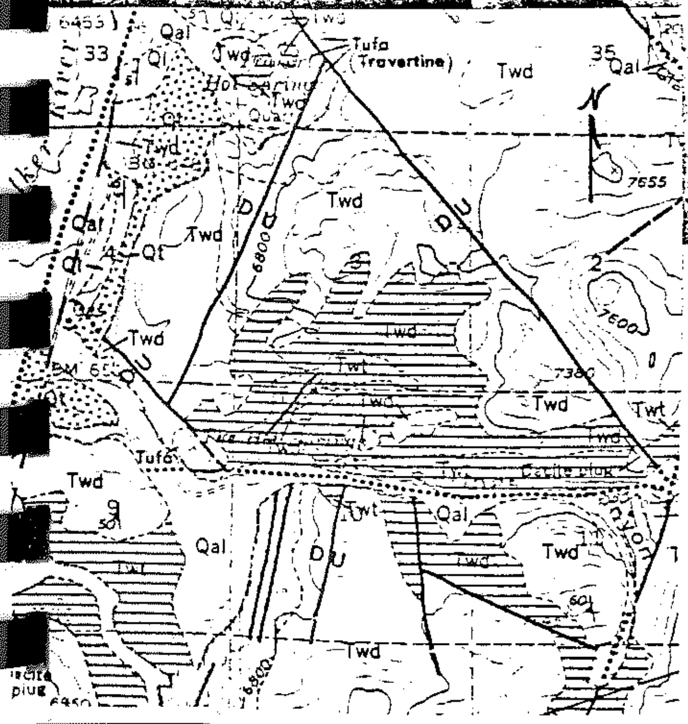


FIGURE 39 — Photocopy of an aerial photograph used by Chesterman to map faults in area southeast of Bridgeport. The faults are numbered according to the order they are discussed in the text. Geologic map at left shows same area as on photograph (after Chesterman and Gray, 1975).

in the present report) against dacite (not shown on the published map). Observations made during the present study suggest, however, that the contact is depositional. Chesterman showed this fault offsetting ledges of outwash sediment near the common boundary between sections 27, 28, 33 and 34. A field check of well-exposed strata just southeast of these ledges, and through which this fault should pass, did not indicate that the strata are offset.

3) A northeast-trending fault is shown to connect Travertine Hot Springs and The Hot Springs. Because the fault is confined soley to dacite , there are no offset units shown on the map. A weak topographic lineament appears on areal photographs and should be field checked to confirm the existence of this fault.

4) Evidence for this northwest-trending fault is similar to that for fault No. 3 and needs field checking.

5) Chesterman showed lake beds in fault contact with dacite on this north- northeast-trending fault just off the north edge of Chesterman and Gray's (1975) map. Field observations indicated that volcanic rock, not lake beds, is exposed here. There is a topographic lineament suggestive of the fault, however.

6) Shown as concealed, this fault runs the length of the main part of Hot Springs Canyon. The distinct linearity of the canyon, the apparent truncation of several north-south-trending faults, and the differences in amounts of hydrothermal alteration shown at the ground surface on each side of the fault, all serve as evidence of the fault. Gravity and magnetic surveys conducted in this area by the California Division of Mines and Geology in 1978 did not show

any distinct anomalies where the survey lines cross faults 2, 3, or 5.

In summary, much of the evidence for Chesterman and Gray's (1975) faults in this immediate area does not appear to be conclusive and indicates that the area needs to be mapped in greater detail before drilling is attempted.

Local Faults Recognized During the Present Study

Several small faults and two queried large faults were recognized during the present study (Plate 6). Trends are either northeasterly or vary slightly from east to west of north. Dips are steep to very steep and are either to the west or east.

The best exposures of fault planes are in the uppermost of two sand and gravel quarries (shown approximately by the "gravel pit" on Plate 6) southeast of Bridgeport. Here, three faults are exposed in a straight, near-vertical cut, which is several tens of meters long. Because of their small offsets and limited exposure, the faults are not shown on Plate 6. They offset near-horizontal layers of weakly consolidated Quaternary sands and pebbly gravels. The following table gives data on the faults, which are listed from northwest to southeast as they appear in the quarry:

	NORTHWEST		SOUTHEAST
	Fault A	Fault B	Fault C
Strike	N4W	N3E	N5W
Dip	75NE	75NW	65NE
Separation	~1 meter	~1 meter	~1/2 meter
Downside	NE	NW	NE
Hydrothermal Alteration	None observed	None observed	None observed

Of these three faults, only Fault B was observed to cut the entire exposed section of sediment. Fault A was observed to be overlain by unfaulted sediment. It was not determined if Fault C cut the entire exposure because of difficulty of viewing the fault trace and because of poorly-defined horizons in the upper part of the quarry cut.

In the northeast corner of section 33, a queried fault strikes just east of north. Possible evidence for this fault includes the presence and absence of cobble conglomerate on opposite sides of the fault and the possible offset of two resistant ledges of indurated sandstone at the boundary between sections 28 and 33. This evidence is weak, however, because both phenomena could also be explained by the deposition of gravels on a surface with topographic relief. If this fault does exist, it probably dips very steeply as indicated by the straight line of its trace across the topography.

Approximately 0.5 km northwest of Travertine Hot Springs is a northeast-trending fault that juxtaposes andesite and Quaternary outwash sediments. Fragments of opalite and volcanic glass are present along this contact.

A lineament observed on aerial photographs trends about N35E and extends from the middle of section 4 almost to the section line between sections 27 and 34. This may be a fault with the northwest side downthrown as indicated by topographic highs and lows. Mapping of the contact in section 34 between the dacite and overlying outwash sediments indicates minimal, if any, offset of this contact across the lineament.

Dacite is absent northwest of a northeast-trending line that passes through the southeast quarter of section 33 and the northwest quarter of section 34. This line is plotted on Plate 6 as a queried fault, although more detailed field examination will be necessary to insure that the contact is not depositional. In other words, the dacite exposed today may have been a bedrock high against which the outwash sediments were deposited. River terraces could have been cut into this bedrock, and then subsequent aggradation could have deposited thick amounts of sediment on the terraces, thus giving the appearance of a fault contact.

Along the dirt road in the very southeast part of section 33 (approximately at the "O" in the name "Travertine Hot Springs" on Plate 6) is a 3-meter wide zone of strongly-fractured, oxidized dacite breccia. The zone appears to be cut by two crossing sets of fractures. One set strikes approximately N80W and dips 80NE while the other set strikes approximately N5W and dips 85SW. Although a boulder of this material found along the side of the road exhibited slickensides, it is not known if this zone represents a fault.

HYDROLOGY

There is very little published information of the hydrology of the Bridgeport Valley-Bodie Hills area. Some data is available from Bader (1969) and from the California Department of Water Resources Bulletin 130 series. The following data on the Bridgeport Valley hydrographic basin are derived from Bader (1969):

Area of basin: 260 km^2

Water-bearing units: alluvium, which ranges in age from late Tertiary to Holocene

Principal recharge areas: glacial moraines, alluvial fans on margin of valley

Rate of recharge: moderate

Maximum depth to water: 1 meter

Minimum depth to water: 0 meters

Direction of movement of ground water: northward

Principal chemical constituents: Ca, Na, HCO_3, SO_4

Range of total dissolved solids (ppm): 74-2,030

Uses as of 1967: domestic, stock, irrigation

The files of the California Department of Water Resources were researched for drillers' reports on the Bridgeport area, but few reports were found because of the few wells drilled there and because many drillers failed to submit reports. Of the three wells for which information was found, the deepest was about 60 meters and first struck water at 10 meters; it flowed at about 57 liters/minute after its completion in the late 1950's. The next deepest was about 30 meters and first reached water at about 12 meters. Both appear to have bottomed in Quaternary outwash sediment. All three wells are upslope from the valley bottom, which may explain the greater depth to ground water than that reported above by Bader (1969).

Because of their high permeability, which is caused both by fractures and by the brecciated character, the andesites east and southeast of Bridgeport probably serve as good areas of recharge, but serve as poor aquifers. Numerous springs are present in the hills to the east; most are probably fault-controlled.

EVIDENCE OF THE AREA'S GEOTHERMAL RESOURCES

Heat Flow

Apparently no heat flow measurements have been taken in the Bridgeport Valley or Bodie Hills. Sass and others (1971) contoured the general region as about 1.5 HFU, which is about average for a continental region.

Seismicity

Figure 40 shows the epicenters of earthquakes of magnitude 2 and greater superimposed on the Walker Lake Sheet of the Geologic Atlas of California (1963), scale 1:250,000. The epicenters are for the period 1900-1974 and are taken from the Earthquake Catalog of the California Division of Mines and Geology (1978). Because instrumentation was and is sparse in this part of California and Nevada, the locations may be in error by as much as several kilometers.

The most seimic activity appears to be in the mountains that border the north half of Bridgeport Valley. Only one epicenter is shown in the immediate area of interest - near The Hot Springs; activity is almost nil in the Bodie Hills proper.

Microseismic studies apparently have not been done in the area.

Volcanism

The Bodie Hills were formed largely from the accumulation and subsequent upwarping of piles of volcanic rock that were erupted locally from approximately 8 to 10 million years ago. After these eruptions, volcanism ceased until about 5.5 million years ago when several bodies of rhyolite and rhyodacite were intruded into the

FIGURE 40 — Epicenters of earthquakes in the Bridgeport - Bodie Hills area. Source of data: Calif. Div. Mines and Geology, 1978. Base map after Calif. Div. Mines and Geology, 1963; Scale 1:250,000.

◯ Magnitude 5 ◯ Magnitude 4 ○ Magnitude 3 older volcanic rocks. These silicic rocks probably represent the youngest exposed volcanic rocks in the western Bodie Hills. The center of this intrusive activity appears to have been at Big Alkali, a collapse cadlera about 5 km southeast of Bridgeport. Figure 41 shows this eruptive center as well as other established and postulated eruptive centers of the region.

The distribution of the rhyolite-rhyodacite plugs suggests that the associated magma chamber was extensive under the western Bodie Hills. In the local area near Bridgeport, the log of the exploratory geothermal well at The Hot Springs reported that rhyolite was encountered intermittently over a depth interval of about 100 meters. This log should be treated with caution, however, because workers in the area have misidentified intensely altered and silicified andesite as rhyolite.

Thermal Springs

Although there is an abundance of springs in the Bodie Hills area, few are thermal. The four sites of definite or possible thermal springs are discussed below and shown in Figure 42.

Travertine Hot Springs:

Situated on a terrace of travertine about 2 km southeast of Bridgeport, this group of three main springs and many seeps is the hottest in the Bridgeport-Bodie Hills area. Maximum recorded temperatures in late 1977 were 80°C at the surface of one pool and 82°C at 50-60 cm depth in another pool. The estimated rate of flow for the entire system was only 40-50 liters/minute. Pertinent geochemical data collected by Mariner and others (1977) from these springs are shown in Tables 20 - 25.

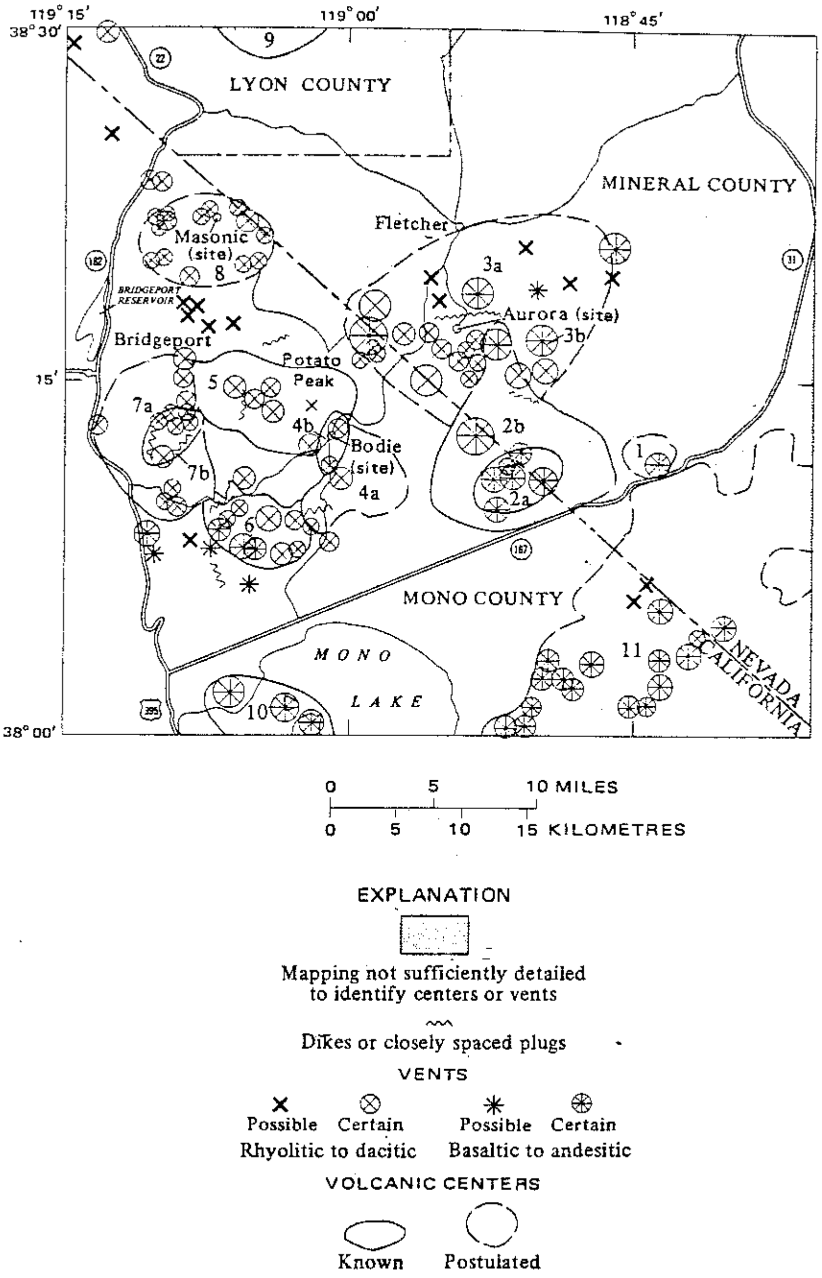


FIGURE 41 – Eruptive centers in the Bodie Hills area. After Kleinhampl and others (1975).

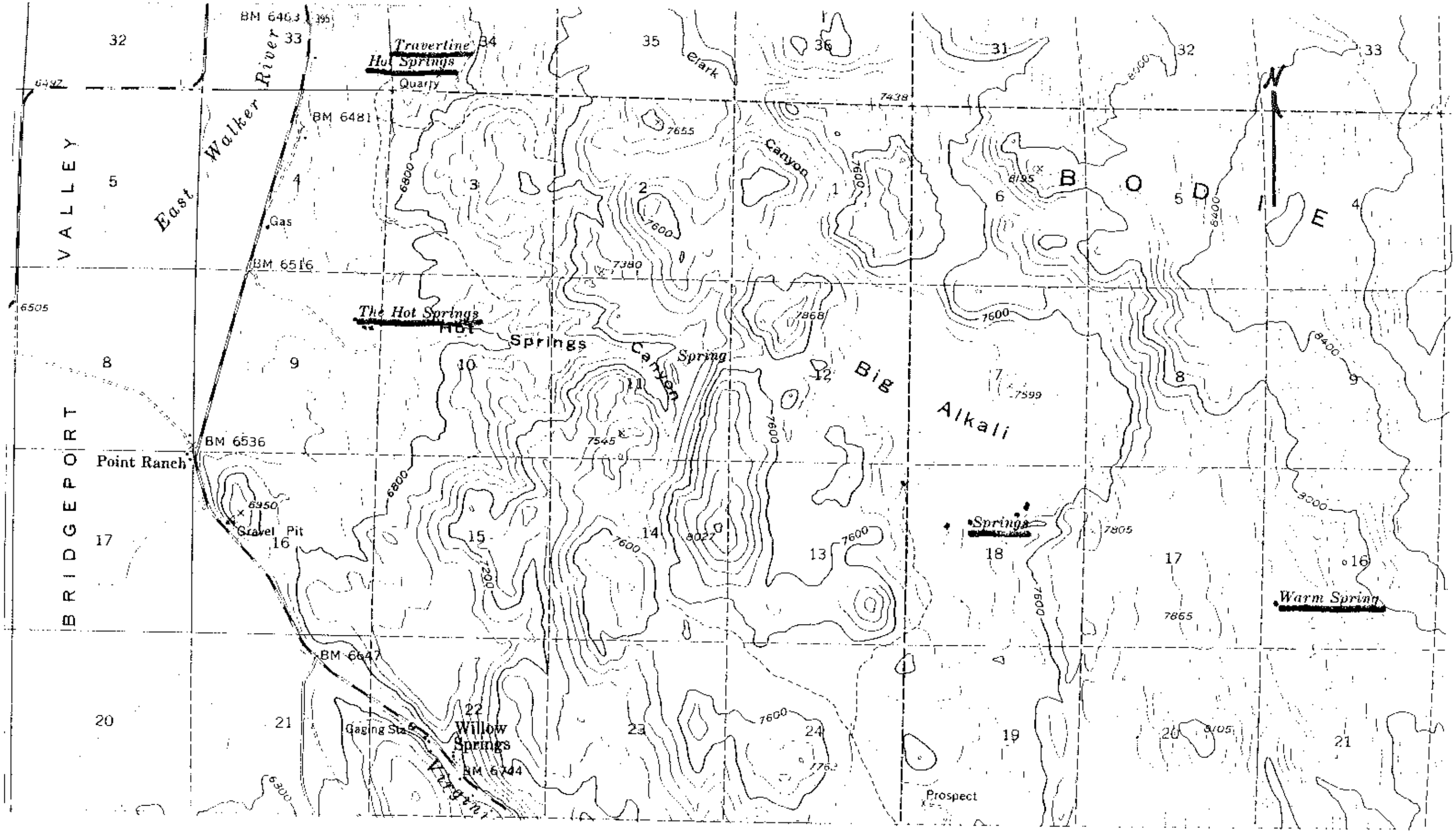


FIGURE 42 – Thermal springs in the Bodie Hills. Locations of springs outlined in red. Those in Big Alkali are not thermal today, but were reported by Russell (1884) and Waring (1915) to be thermal in the 19th Century. Map scale 1:62,500.

TABLE 20 - [illegible]riptive Da[illegible] for [illegible]vert[illegible] Hot [illegible]ings [illegible] Th[illegible] Sp[illegible]

(All data in Tables 20-25 after Mariner and others, 1977)

Spring	Location	Description
2. The Hot Springs---------------------------	NE¼sec. 9, T. 5N., R. 25E.	Gassy springs issuing through travertine mounds; flow rate less than 100 Lpm.
3. Travertine Hot Springs-------------------	SW¼sec. 34, T. 5N., R. 25E.	Gassy springs issue along the western end of several long parallel travertine ridges; flow less than 50 Lpm.

Table 21--Chemical analyses of sampled thermal springs

[Concentrations are in milligrams per liter]

Spring	Temperature (°C)	pH	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Alkalinity as bicarbonate (HCO_3)1/	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Boron (B)	Dissolved constituents2/
The Hot Springs---------------------------	40	7.03	65	76	18	1,100	62	2.8	1,880	910	210	4.3	11	4,394
Travertine Hot Springs-------------------	69	6.73	100	64	18	1,100	55	2.5	1,800	920	200	4.5	9.9	4,324

Table 22-Mole ratios of major and minor constituents in the thermal waters

[Dashes indicate that one of the constituents used in the ratio was less than the detection limit.]

Springs	pH	Dissolved solids (mg/L)	Cl/SO_4	Cl/HCO_3	$(F/Cl)x10^2$	$(B/Cl)x10^2$	(/Ca)/Na	$(K/Na)x10^3$	$(Li/Na)x10^3$	$(Mg/Ca)x10^2$
The Hot Springs---------------------------	7.03	4,394	.63	.19	3.8	17	.91	33	8.4	39
Travertine Hot Springs--------------------	6.73	4,323	.59	.19	4.2	16	.83	29	7.5	46

Table 23 --Measured spring temperatures and estimated thermal-aquifer temperatures based on the chemical composition of the thermal spring waters

[All temperatures are in °C]

Spring	Spring temperature	Estimated aquifer temperatures for various geothermometers[1]							Comments
		Quartz	Chalcedony[2]	Alpha-cristobalite[2]	Amorphous silica[2]	Na-K	Na-K-1/3Ca	Na-K-4/3Ca	
The Hot Springs----------------------------	40	114	85	66	30	125	172	177	Low flow rate; precipitation of calcium carbonate; Na-K-Ca geothermometer in doubt.
Travertine Hot Springs--------------------	69	137	107	86	48	115	167	176	Low flow rate; precipitation of calcium carbonate; Na-K-Ca geothermometer in doubt.

[1] Underlined numbers are those favored by the authors.

[2] Adjusted for dissociation of H_4SiO_4 at spring temperature and pH.

Table 24--Trace constituent concentrations in thermal waters

[Concentrations are in milligrams per liter; dashes indicate the absence of data]

Spring name	Sulfide (as H_2S)	Aluminum (Al)	Rubidium (Rb)	Ammonia (as N)	Cesium (Cs)	Manganese (Mn)	Copper (Cu)	Nickel (Ni)	Mercury (Hg)	Zinc (Zn)	Iron (Fe)
The Hot Springs--------------------------	<1	.003	.42	<.1	.5	.09	.01	.02	.0001	.20	.02
Travertine Hot Springs------------------	<.5	.004	.40	<.1	.4	<.02	.02	.02	<.0001	.18	.05

Table 25 --Composition of gases issuing from the thermal springs

Spring	Percent by volume				
	O_2+Ar	N_2	CH_4	C_2H_6	CO_2
The Hot Springs----------------------------	1.1	3	<.1	<.1	85
Travertine Hot Springs--------------------	0.4	1.1	<.1	<.1	93

The Hot Springs:

About 3 km south of Travertine Hot Springs is a group of thermal springs and seeps on a travertine-encrusted terrace. These are substantially cooler than Travertine Hot Springs with a maximum recorded temperature of only 44°C in 1977. The cumulative rate of flow from the entire group was estimated to be less than 100 liters/minute. Geochemical data for these springs are also shown in Tables 20 - 25.

Warm Spring:

Situated in section 16, T 4N, R 26E, this spring had a maximum temperature of only 25°C in 1977. The rate of flow was estimated at only a few liters/minute. A chemical analysis of this water as well as new analyses of several samples each from Travertine Hot Springs and The Hot Springs, all performed by the California Division of Mines and Geology, are presented in Table 26.

Springs in Big Alkali:

There are many cold springs on the south and west sides of Big Alkali, a flat basin between The Hot Springs and Warm Spring. Both Russell (1889) and Waring (1915) reported these springs to be thermal, however. Russell did not discuss them in his text, but did show them as "warm springs" on an accompanying topographic map. Waring reported "thermal" water in Big Alkali (known then as "Warm Springs Flat"), but gave only crude estimates of temperature (38°C) and flow. Neither worker visited the springs in person. These reports and the present conditions indicate that the springs were probably mildly warm during the last century, but have since cooled off, a phenomenon that is not unusual. In contrast, Travertine Hot

Table 26. PARTIAL CHEMICAL ANALYSES OF WATER FROM THERMAL SPRINGS IN BRIDGEPORT-BODIE HILLS AREA
(Analyses performed in December, 1977 at geochemical laboratory of CDMG)

Spring	Date Sampled	Temp. °C	As	Ca	Fe	Hg	K	Mg	Na	P	Si	(all concentrations in ppm) (T-trace)
Travertine	10/77	70	1.1	66.4	2.8	T	84	17.2	1050	0.36	13.5	Three different springs sampled, including hottest spring of entire system.
	10/77	69	1.1	66.2	2.4	T	80	17.4	1000	0.36	13.5	
	10/77	82	0.65	42	2.6	T	84	16.0	1000	0.36	16.3	
The Hot Springs	10/77	35	0.76	73.2	3.8	T	90	17.6	1075	0.29	9.3	Three different springs sampled, including hottest spring of entire system.
	10/77	32	0.70	73.2	2.0	T	88	17.8	950	0.31	13.1	
	10/77	44	0.57	77.0	2.2	T	88	18.0	1050	0.23	7.7	
Warm Spring	10/77	25	0	1.1	1.2	0	2.2	0.2	10.2	0.23	8.4	

Springs have remained at fairly constant temperatures throughout this century.

Geochemistry of the Thermal Springs:

The amounts and types of dissolved solids in waters from both Travertine Hot Springs and The Hot Springs are remarkably similar, which suggests the same source at depth for both groups of springs. Also of note is the comparison of the chemistry of these waters with the chemistry of eleven other thermal springs along the east side of the Sierra Nevada, as determined by Mariner and others (1977). Among these twelve, the Travertine Hot Springs-The Hot Springs analyses indicated the highest amounts of the following: sodium, potassium, magnesium, lithium, sulfate, bicarbonate, boron, rubidium, cesium , and total dissolved solids. They ranked fourth and fifth in amounts of chloride and fluoride, respectively. It is not known at this time if the relative abundance of the alkali metals in these waters is significant. Overall, the thermal waters are dominated by sodium, bicarbonate, and sulfate ions.

From their geothermometric calculations on these waters, Mariner and others (1977) concluded that both Travertine Hot Springs and The Hot Springs may be derived from thermal aquifers with temperatures as high as 107°C. Because of the low rate of flow from both groups of springs, heat is probably lost by conduction such that the water temperatures at the spring orifices are much lower. Both groups of springs are saturated with respect to calcite and both discharge small and sporadic amounts of carbon dioxide.

An unusually large amount of travertine ($CaCO_3$) has been deposited at Travertine Hot Springs in the form of northeast-trending linear ridges, some of which are about 5 meters high and a few hundred meters long. Deep vertical crevices run the lengths of the crests of these ridges and at one point near the end of the crest of one ridge, there is a spring. Most of the water from this spring appears to follow a very shallow channel along the axis of the ridge, which suggests that movement of the water in such a way is responsible for cutting the crevices mentioned above. It is possible that these ridges are formed above well-defined fractures in the bedrock, and the thermal water ascends along these fractures to form the ridges. Waring (1915) believed that travertine was no longer forming, but tufa was being deposited instead. Today, powdery encrustations of tufa are present near many spring and seep orifices.

Although chemical analyses were not made of the springs waters in Big Alkali, the abundance of alkali-encrusted soil suggests that these waters are or were at one time highly-charged with both alkali metals, such as sodium and potassium, and alkaline earth elements, such as calcium and magnesium. Only a few major elements in the water from Warm Spring were analyzed, but of those, the concentrations were remarkably low. For example, of the calcium, potassium, magnesium, and sodium ions, the sodium was the most abundant at only 10 parts per million.

Thermal Wells

The only known wells drilled in the Bridgeport-western Bodie Hills region are a number of water wells near town and the exploratory geothermal well (Bridgeport 1) drilled in 1962 to a depth of nearly 300 meters at The Hot Springs. Of these, only the Bridgeport 1 well is known to be thermal. The maximum reported temperature for the hole was 51°C at 190 meters. A generalized lithologic log of the well is shown in Table 27. It is curious that apparently no drilling has been done at Travertine Hot Springs, an area that seems to offer the greatest chance of finding the highest temperatures of the reservoir.

Data from the district well log records of the California Department of Water Resources and from the report by the California Department of Transportation (1978) indicate that water wells in the immediate area around Bridgeport are not thermal. Approximate locations and depths of these wells are shown in Figure 43. Some chemical data are available for as many as six wells for the period 1963-1967 (California Department of Water Resources Bulletin 130 series) and are shown in Table 28. Of note is the J. Van Dyck well (4N/25E-4F1), which had an unusually high concentration of mineral constituents (total dissolves solids equalled 2,030 ppm in 1965). The nearby C. F. Blackburn well (4N/25E-4B1) is also mineralized, but to a lesser extent. The Van Dyck well is characterized by sodium bicarbonate water, while the Blackburn well is characterized by sodium sulfate water. The former is similar in relative composition to waters from Travertine Hot Springs and The Hot Springs. Both wells, although non-thermal, indicate that thermal fluids may be present at depth, but are being diluted and cooled by cold aquifers composed of meteoric water.

Table 27. LITHOLOGIC LOG OF THE BRIDGEPORT I WELL
(Drilled in 1962 at The Hot Springs by Magma Power Company)

Depth in meters	Description	
0-28	Clay sandstone with shells	
28-72	Clay, sand, volcanic ash	
72-98	Quartzite (41°C at 98 meters - 50 hours of equilibration)	
98-111	Gray white rhyolite with pyrite	
111-125	No record	
125-162	Gray white opalite, red andesite and pyrite	
162-183	Gray rhyolite with some cinnabar and pyrite	
183-194	Gray white rhyolite and pyrite (51°C at 191 meters - 49 hours equilibration)	
194-211	Gray white quartzite with some cinnabar	Basement?
211-222	Gray white quartz	
222-228	No record	
228-237	Gray white quartz	
237-244	No record	
244-251	Gray white quartz	
251-252	No record	
252-264	Gray and white quartz	
264-299	Gray white quartz	

Modified from the official tour report for Bridgeport I, courtesy Magma Power Company.

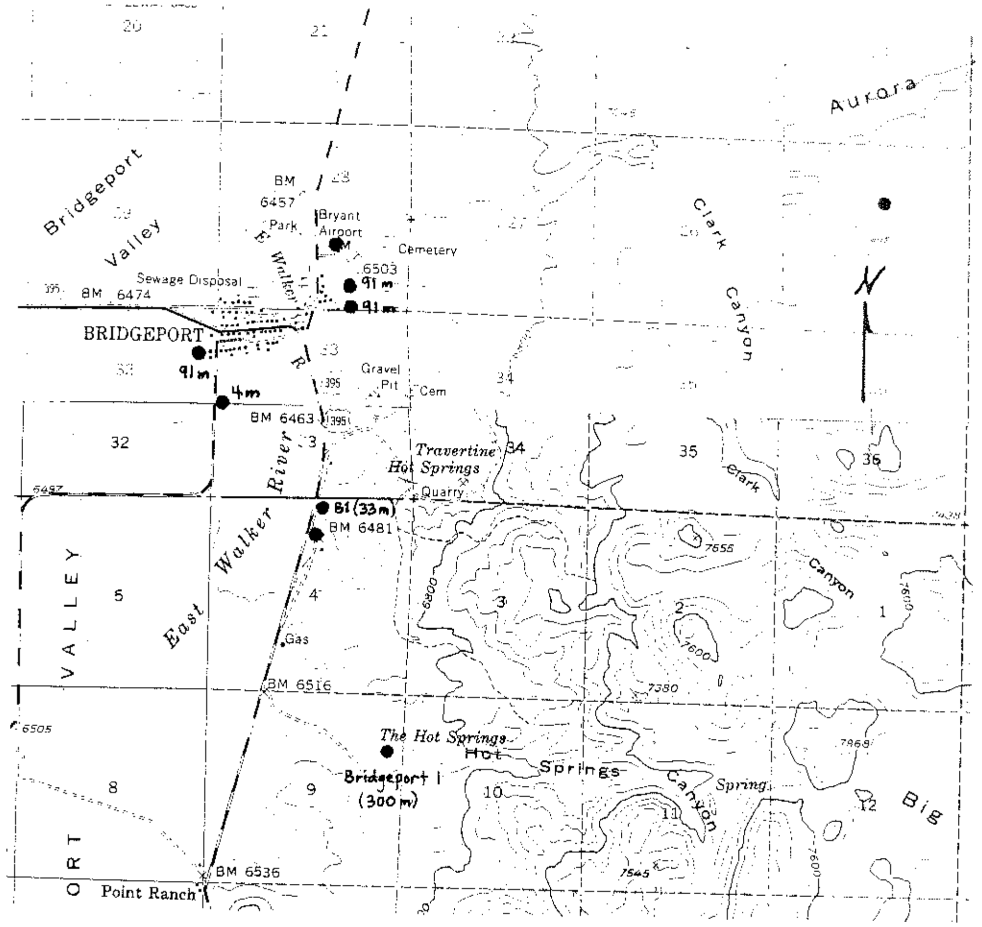


FIGURE 43 – Locations of water wells and the Bridgeport 1 well. The water wells in section 4 are moderately to strongly mineralized. Red dot marks approximate location of well. Map scale 1:62,500.

Table 28. CHEMICAL DATA FOR WELLS IN THE BRIDGEPORT AREA
(Source of data: California Department of Water Resources Bulletin 130 series)

(All constituents in ppm)

WELL OWNER OR NAME OF SOURCE	WELL NUMBER	DATE	SPECIFIC COND. IN MICROMHOS AT 25°C	pH	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	F	B	SiO_2	TDS	%Na
Buckeye Hot Springs	4N/24E-4A1	9/17/63	1450	8.5	12	4.4	315	11	359	347	31	0.0	5.0	1.1	47	974	92
		9/18/64	1470	8.7	20	5	284	20	389	348	31	0.3		0.70		913	
Hunewill Ranch	4N/24E-13E1	9/17/63	99	7.3	14	1.5	3.9	1.6	59	2.9	0.0	0.0	0.1	0.0	18	68	17
		9/18/64	107	7.7	12	3	4	2	56	5	0	0.5		0.0		54	
		8/24/65	98	6.7			3.4		49		0.0					74	
		6/20/66	108	7.7			5.2		54		1.2						
		8/4/67	108	7.9					58		0.5						
C.F. Blackburn	4N/25E-4B1	9/18/63	730	8.0	47	21	87	14	161	243	22	0.0	0.4	0.3	67	600	46
		9/18/64	835	7.3	56	22	77	14	190	242	21	0.7		0.20		526	
		8/24/65	864	8.6	72	13	82	13	160	235	23	1.6		0.3		631	
		6/21/66	326	8.4			26		179		4.2						
J. Van Dyck	4N/25E-4F1	9/17/63	2500	8.2	25	26	580	42	861	589	130	0.0	1.2	5.7	60	1890	85
		9/18/64	3020	7.1	105	30	560	42	1100	585	126	0.0		3.50		1992	
		8/24/65	2890	8.3			581		999		129					2030	
		6/21/66	2760	9.1			587		606		136						
K.C. Stewart	5N/25E-28K1	9/18/63	420	8.2	38	13	36	11	238	34	2.5	1.4	0.1	0.1	45	306	32
		9/18/64	450	8.0	36	14	30	11	228	34	6	0.8		0.00		244	
		8/24/65	442	8.7			34		222		6.6					301	
		6/21/66	500	8.7			38		234		6.7						
		8/4/67	452	8.5					219		7.0						
Bridgeport PUD	5N/25E-28Q1	9/18/63	370	8.1	30	8.6	29	10	190	23	4.3	1.4	0.1	0.1	46	254	34
		9/18/64	332	7.8	29	12	26	10	194	26	5	0.8		0.00		204	
		8/24/65	269	8.4			20		136		4.2					201	
		6/21/66	288	8.5			24		138		8.2						
		8/4/67	282	8.3					153		3.0						
	5N/25E-25G1	9/18/64	127	7.0	14	4	5	2	73	6	0	0.1		0.00		67	
		8/24/65	128	7.9			5.7		71		0.8					88	
		6/21/66	129	8.1			6.2		71		9.4						
		8/4/67	129	7.9					74		0.5						

Hydrothermal Alteration and Mineralization

As shown by Chesterman and Gray (1975), large areas of the Willow Springs Formation in the vicinity of Travertine Hot Springs, The Hot Springs, and Big Alkali are hydrothermally altered (Figure 44); more areas are apparent in aerial photographs. Although he did not study the alteration in detail, Chesterman (1968) made several generalizations about it:

1) The brecciated and tuffaceous rocks were more readily altered than the less porous and less permeable massive lava flows.
2) Fractures allowed extensive alteration because they acted as channelways for migration of the hydrothermal fluids.
3) The massive lava flows showed alteration only where fluids moved through fractures in the lava; otherwise, the flows acted as impermeable barriers.

The last generalization is important because, although alteration may not be visible at the ground surface, it may be present at depth beneath impermeable massive lava flows.

Most of the alteration involved either bleaching or replacement by opaline silica. One cliff in section 30, T 4N, R 26E, is composed almost entirely of opaline silica. The cliff was once mined for the silica and now appears as a blinding-white cliff in direct sunlight. The rock is friable and of extremely low density.

Just northeast of the cemetery along the boundary between sections 33 and 34 near Bridgeport, several pieces of Quaternary outwash gravel totally or partially altered to opal were found in the bottom of a gully. Although outcrops of this material were not recognized, the opalization of the gravel is important because it suggests that hydrothermal alteration was active in

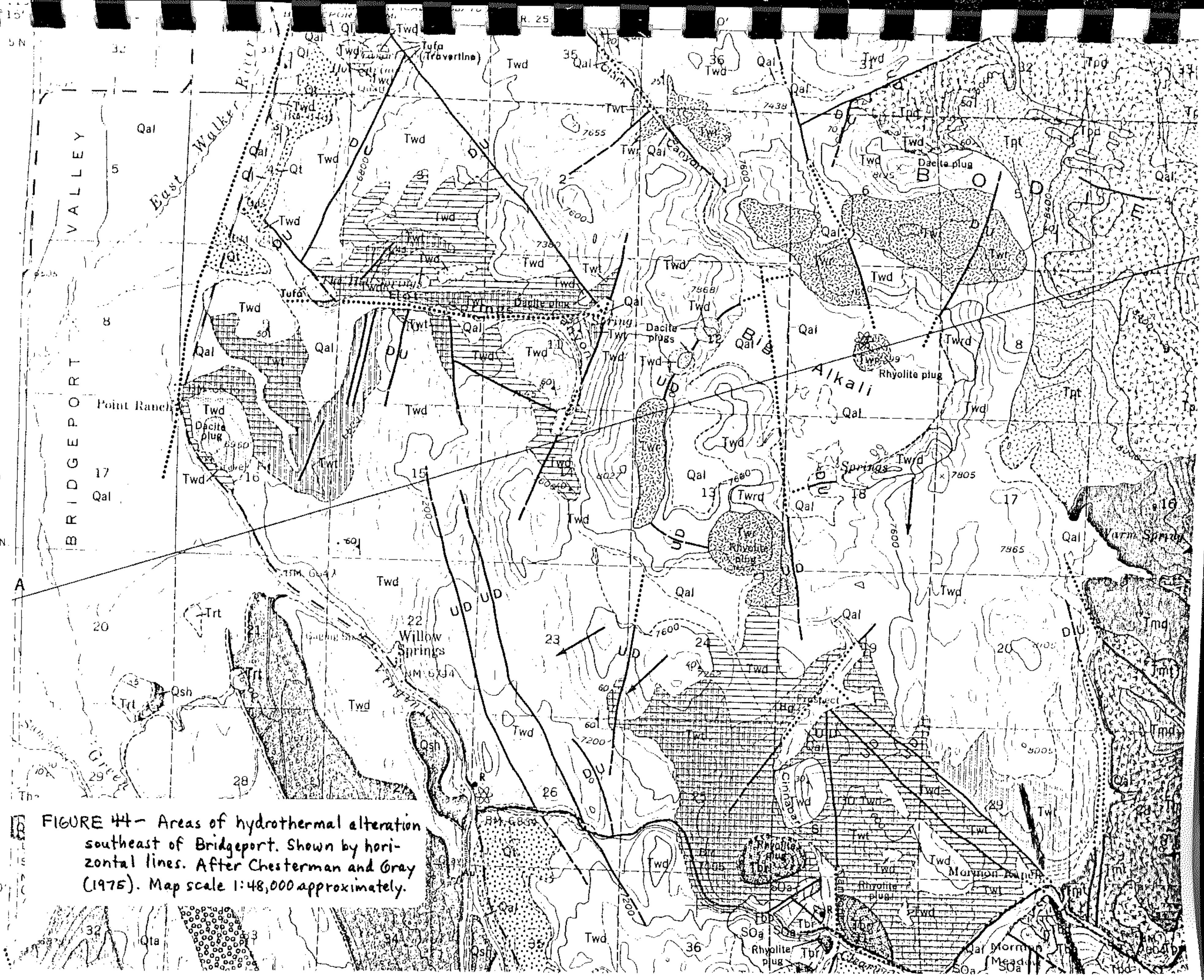


FIGURE 44 – Areas of hydrothermal alteration southeast of Bridgeport. Shown by horizontal lines. After Chesterman and Gray (1975). Map scale 1:48,000 approximately.

this locality during the Quaternary; alternatively, the gravels could have been opalized at some distant site and then transported to the present site.

Mineralization in this local area includes deposition of cinnabar and pyrite. The former has been recognized both at the surface and in the Bridgeport 1 well. Two prospects for cinnarbar are mentioned in the literature: an unnamed one in section 19, T 4N, R 26E (Chesterman and Gray, 1975) and the Wedertz claim in section 26, T 4N, R 26E (Sampsom and Tucker, 1940). No data were given for either. Chesterman (1968) reported that cinnabar was found at several places along Cinnabar Creek.

The log of the Bridgeport 1 well reported cinnabar and "opalite" at intervals from 125 meters to 211 meters. Pyrite was reported at intervals from about 98 meters to 194 meters. Rhyolite was reported as the country rock associated with these deposits, but this may in reality be strongly-altered andesite. Kleinhampl and others (1975) reported some misidentifications of rhyolite for intensely bleached and silicified andesite.

The age or ages of the alteration and mineralization are difficult to determine because of the paucity of marker units. If we assume that the altered dacites are approximately 8 million years old, we can conclude that the alteration and mineralization took place no earlier than that time. As discussed earlier, rhyolite intrusions about 5.5 million years old are present in the Bid Alkali area; most or all of the alteration may have been associated with this igneous activity. As all or nearly all of the Quaternary outwash deposits are not affected by alteration, the bulk of the alteration probably took place at least a few million years ago.

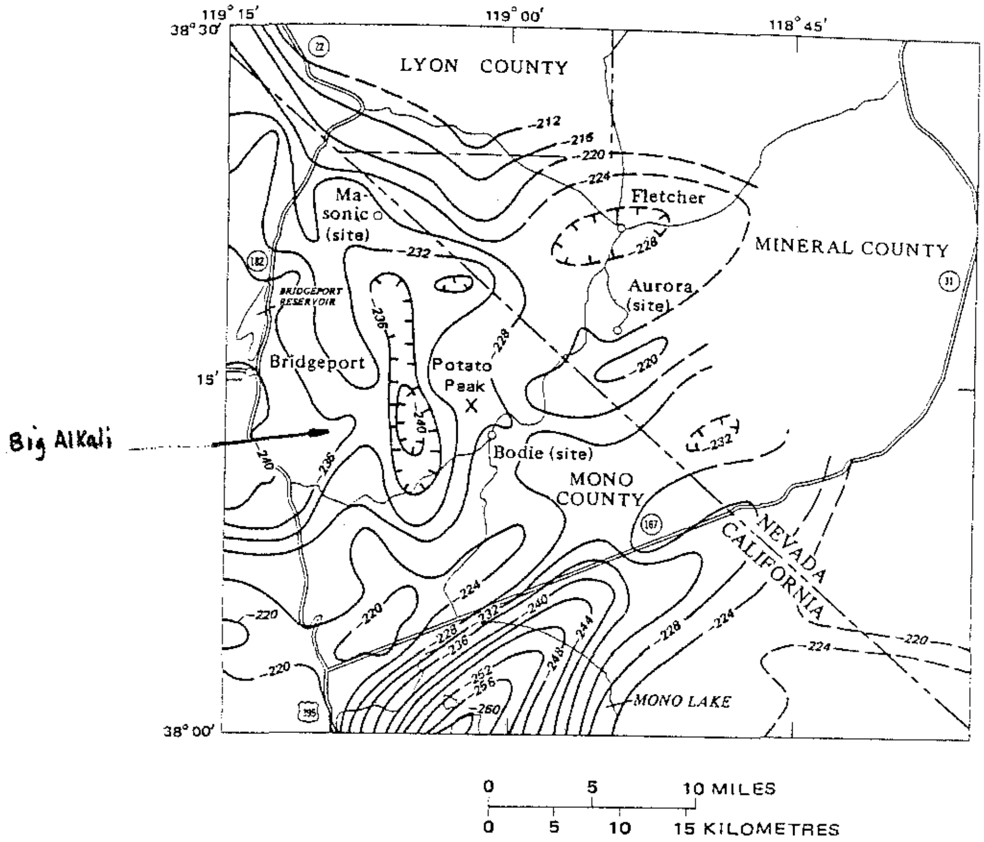
Geophysical Surveys

Two geophysical surveys have been conducted in the Bridgeport-Bodie Hills area, one regional study by Kleinhampl and others (1975), which covered nearly the entire Bodie Hills, and the other a local study by the California Division of Mines and Geology, which covered the small area that includes Travertine Hot Springs and The Hot Springs.

The regional gravity and magnetic contours as determined by Kleinhampl and others (1975) for the Bodie Hills are shown in Figure 45 and Plate 5, respectively; no seismic or resistivity surveys were performed. The gravity map shows a prominent north-south-trending low between Potato Peak and Big Alkali. To the west of this low is a north-south-trending high that is partially re-entered in its middle by a low, which correponds with Big Alkali. Somewhat off-center from Big Alkali to the northeast is a magnetic high.

Comparison of the distribution of basement rock and volcanic rock with the gravity anomalies suggest that basement highs are responsible for the gravity highs. For example, portions of the north-south gravity high correspond with high density basement exposed at the ground surface. On the other hand, the north-south gravity low just to the east appears to correspond with the less-dense Cenozoic volcanic rocks. The juxtaposition of these two gravity zones and their associated rock types suggests a major north-south fault in the basement with the east side downdropped.

The east-northeast-trending zone that includes The Hot Springs, Big Alkali, a saddle in the north-south gravity high, and the center



EXPLANATION

-220

Gravity contour

Dashed where approximately located. Contour interval 4 milligals

-240

Gravity contour enclosing area of low gravity

Dashed where approximately located

FIGURE 45 – Bouguer gravity map of the Bodie Hills area. After Kleinhampl and others (1975).

of the north-south gravity low appears to represent a basement low, possibly a graben, filled with lower density volcanic material. The Bridgeport 1 well, which is within this zone, may or may not have reached basement. The lithologic log (Table 27) mentioned "quartzite" and "quartz" from about 200 to 300 meters depth, but it is unknown whether this description meant metamorphic rock (basement) or silicified volcanic rock. The weak gravity low and strong magnetic high associated with Big Alkali may represent deposits of alluvium in the bottom of Big Alkali underlain by a completely solidified body of strongly magnetic rock.

Geophysical Surveys by California Division of Mines and Geology*:

During 1978, gravity and magnetic surveys, supplemented by limited shallow resistivity and seismic refraction surveys, were completed in the area just east and southeast of Bridgeport. The survey included six detailed gravity lines, seven ground magnetic lines (total intensity), one electrical resistivity profile, two shallow resistivity soundings, and one short seismic refraction line, the latter used to investigate a possible fault. The locations of all lines are shown in Figure 46. The data were obtained with the following instruments:

Gravity	LaCoste and Romberg geodetic gravity meter (G-129)
Magnetic	Geometrics model G 816 total intensity magnetometer
Resistivity	Direct current resistivity system
Seismic Refraction	Dresser Industries RS-4 twelve-channel system

The gravity data were tied to a base station in Bridgeport (Chapman, 1966)

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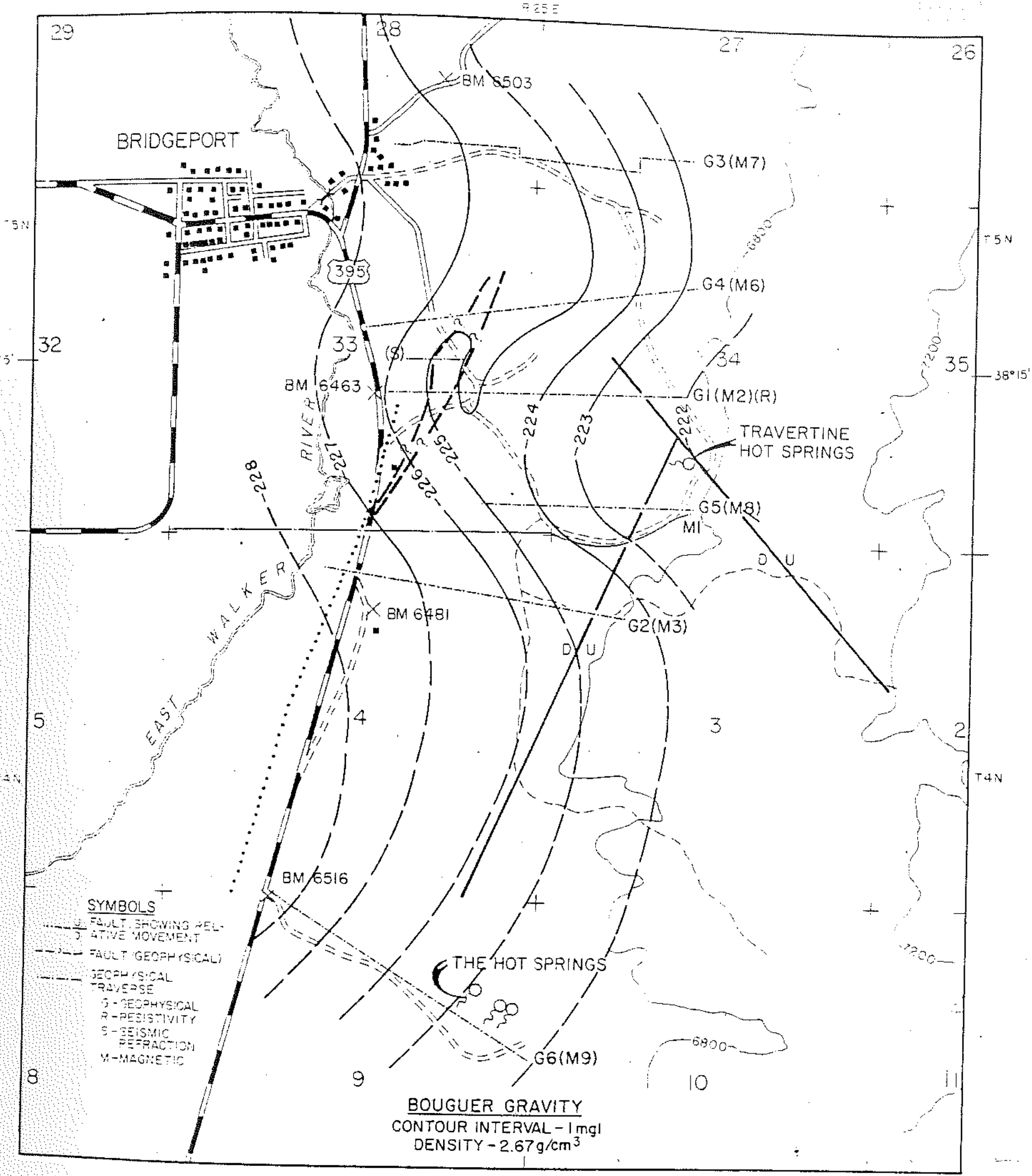
* Modified from an unpublished report by Gordon W. Chase and Rodger H. Chapman.



TRAVERTINE HOT SPRINGS
MONO COUNTY, CALIFORNIA
CALIFORNIA DIVISION OF MINES AND GEOLOGY
1979

FIGURE 46 – Bouguer gravity southeast of Bridgeport. Locations of geophysical traverses also shown.

and were reduced to complete Bouguer anomalies using reduction densities of 2.67 and 2.50 g/cm^3.

The gravity and magnetic traverses (G and M, respectively) generally used the same stations along traverses, although the gravity station interval was 61.0 meters while the magnetic station interval was 30.5 meters. One additional magnetometer line and a few line extensions were also run. The resistivity profile (R1) was run along one line (gravity line G1) and used a Wenner configuration with a 30.5-meter spacing interval. In addition, two shallow electrical soundings were obtained at stations R2 and R3.

The seismic profile (S-1) had a total length of 244 meters and comprised three 84-meter spreads (less one station). The spacing of geophones was 7.6 meters. The energy source was a free-falling weight of about 180 kilograms, dropped approximately 1.2 meters to a heavy steel plate.

As shown in Figure 46, gravity values decrease generally toward the west. This decrease is associated with a large negative anomaly that characterizes Bridgeport Valley (Oliver and others, 1973; Kleinhampl and others, 1975). Figure 46 also shows a conspicuous bowing of the one milligal contours toward the west along an east-west line through Travertine Hot Springs.

Figure 47 is a residual gravity contour map (contour interval of 0.25 milligal) constructed by removal of the estimated regional trend. The map shows two positive anomalies of about 2 milligals each, the larger one centered just west of Travertine Hot Springs and the other near the west end of line G1. The causes of these anomalies are not known, but the large one could represent either a basement high or

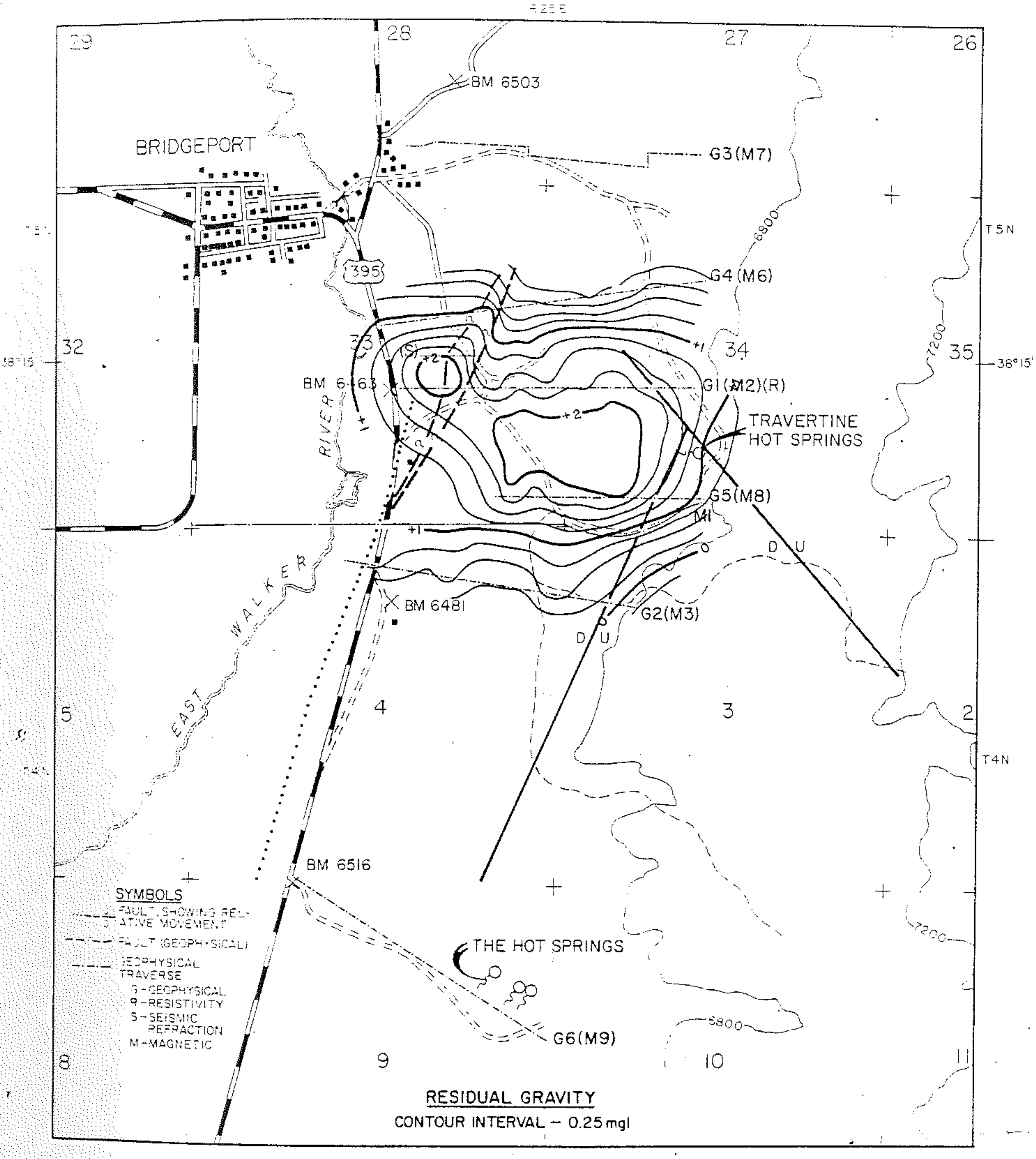


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FIGURE 47 – Residual gravity southeast of Bridgeport.

a buried intrusive mass, possibly the source of heat for the hot springs.

The magnetic contour map (Figure 48) shows a number of east-west, elongate positive and negative anomalies. The anomalies are believed to be caused by the intermediate volcanic rocks that underlie much of the area. Some anomalies may represent faults. The steep magnetic gradients near the west ends of lines M-1, M-2, and M-6 appear to represent a fault or steep depositional contact. The causes of the sharp magnetic low near the east end of line M-6 and the positive anomaly on the east end of line M-7 are not known.

The resistivity profile on Plate 7 shows a general westward decrease in resistivity. A change in the profile occurs about 300 meters east of the west end of the line and may be closely associated with the small positive gravity anomaly shown in Figure 47. The steep magnetic gradient on the associated magnetic line occurs about 61 meters west of the change in the resistivity profile. All three anomalies may represent the same fault zone. The seismic refraction line, about 150 meters north of the line G-1 and shown on Plate 8, was run to investigate this possible fault zone. The line shows a possible bedrock high as well as a low-velocity zone near the center of the traverse. The latter could represent a crushed zone possibly associated with faulting.

The profiles of gravity lines G1 and G4 and magnetic lines M2 and M6 were examined for evidence of the possible northeast-trending fault speculated to pass through the southeast quarter of section 33 and the northwest quarter of section 33. As can be seen from Plates 8 and 9, there are breaks in the profiles of lines G1, G4,

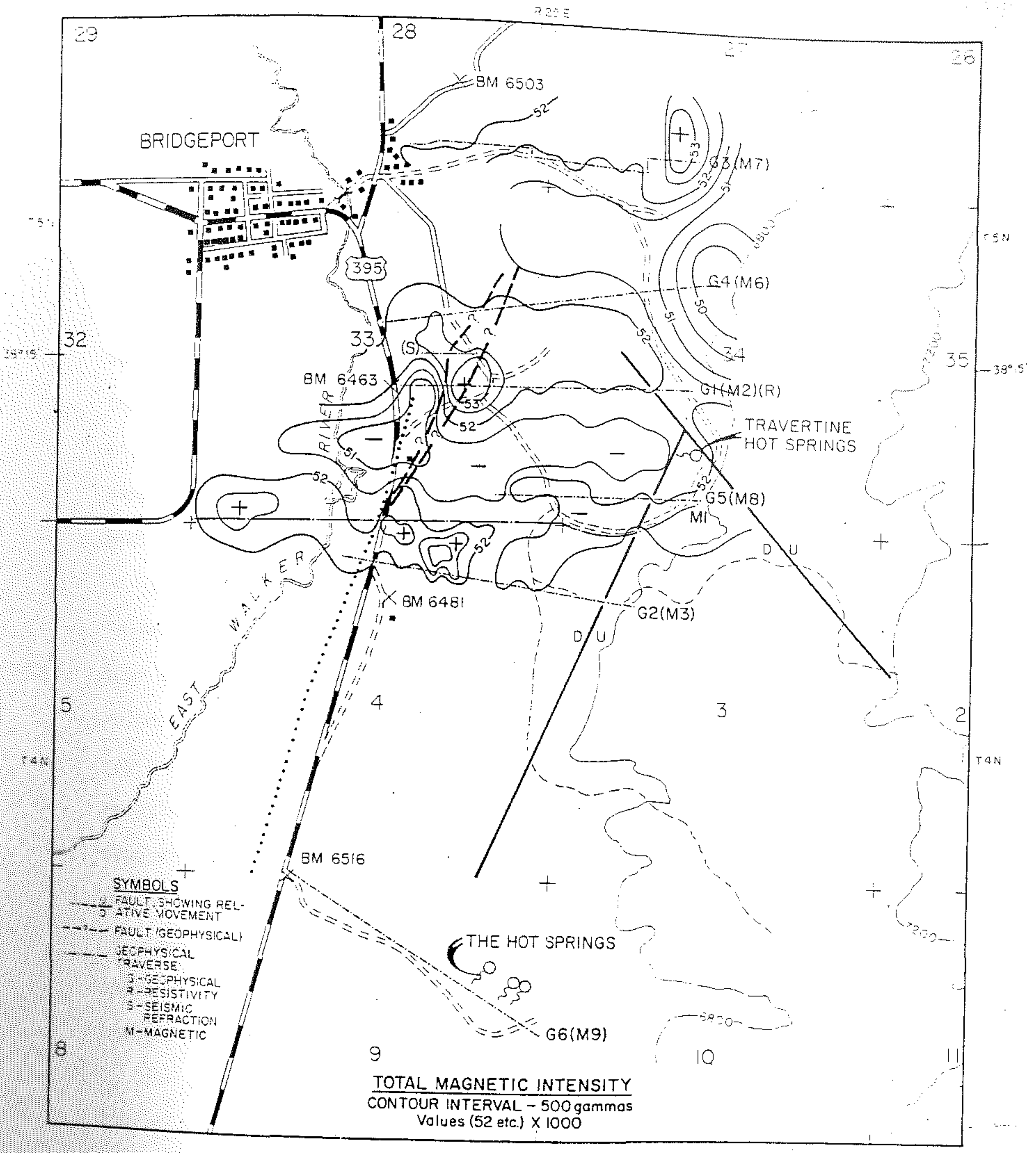

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FIGURE 48 - Magnetic contours southeast of Bridgeport.

and M2 where they intersect the speculated trace of the fault. The breaks appear to be too small, however, to conclusively indicate faulting.

ORIGIN OF THE GEOTHERMAL ANOMALIES AND ESTIMATION OF RESERVOIR PROPERTIES

Both the cause and extent of the anomalously high subsurface heat in the Bridgeport-western Bodie Hills area are still unresolved. The lack of heat flow data, sparse evidence of current geothermal activity at the ground surface, just one exploratory drill hole, and data from geophysical surveys and water wells have shed only meager light on what exists at depth.

The amount and character of the dissolved solids in waters from Travertine Hot Springs, The Hot Springs, and the Van Dyck well suggest that some of the water may be volcanic in origin; ions of sodium, chloride, and sulfate are abundant while ions of fluoride, boron, and lithium are present in significant amounts. The similarity of the types and relative abundances of the ions found at these three sites also suggests that they were derived from the same source, which may underlie the area outlined in Figure 49. In contrast, the extremely low amount of dissolved solids in water from Warm Spring suggests that the water there is strictly meteoric and may be heated by circulation at depth along a fault that penetrates a zone of average geothermal gradient.

The numerous fractures in the Bodie Hills and the near-absence of thermal springs, except near Bridgeport, indicate that if a body of magma is responsible for the geothermal anomalies, its effects at the ground surface are apparent only in the northwest part of the

Bodie Hills near Bridgeport. Otherwise, one would expect more thermal springs in the remainder of the hills because of the many opportunities for water to ascend along faults and joints after being heated at depth.

Geothermal anomalies may occur under the flat floor of Bridgeport Valley, but the cold-water aquifers are so extensive and voluminous that they dilute and cool any evidence of the anomalies. The few drillers' records available for wells on the valley floor indicate non-thermal waters.

Renner and others (1975) very crudely estimated the properties of the geothermal reservoir at Travertine Hot Springs. They estimated the subsurface area to be 1.5 km^2 and the thickness to be 1.5 km, resulting in a reservoir volume of 2.25 km^3. They computed the heat content of the reservoir to be 0.42×10^{18} Joules. Brook and others (1979) took into account the location of The Hot Springs and increased the estimation of the reservoir volume to $3.3 \pm 0.26 \times 10^{18}$ Joules, an increase of about double the estimate of Renner and others (1975).

Mariner and others (1977) used geothermometry to estimate the temperature of the aquifers that supply Travertine Hot Springs and The Hot Springs. Their respective favored estimates of 107°C and 85°C were determined by use of the chalcedony geothermometer; Table 23 shows their other geothermometric estimates. More recently, Brook and others (1979) made the following estimates of reservoir temperature for the Travertine Hot Springs area:

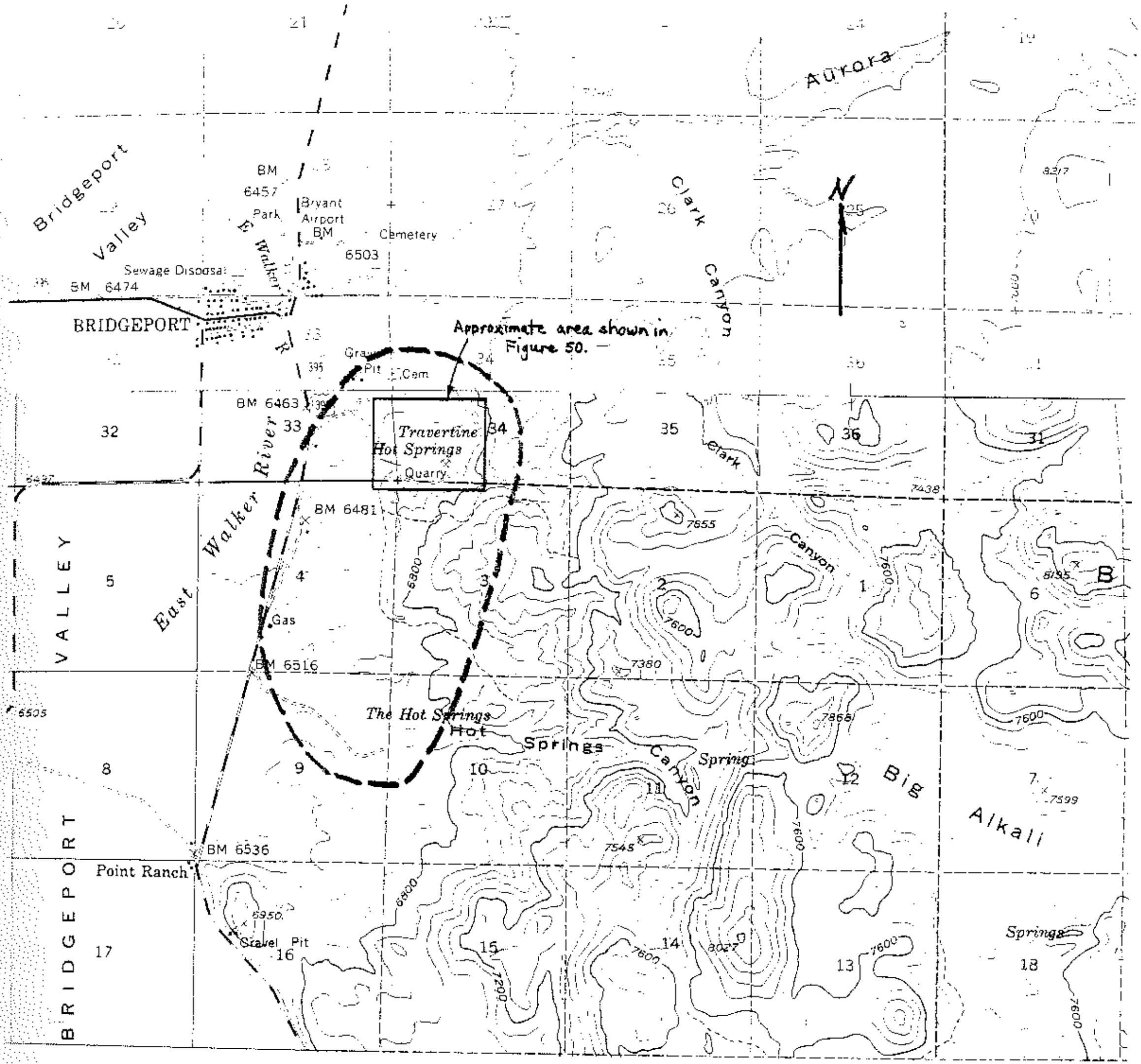
Geothermometer	Estimated Temperature °C
Na-K-Ca (Mg corrected)	87
Chalcedony	110 (most likely temperature)
Quartz conductive	137
Mean value	111±10

POTENTIAL FOR GEOTHERMAL APPLICATIONS IN THE AREA

The Bridgeport-western Bodie Hills area is a sparsely-settled region, the economy of which is based mainly on ranching and tourism. Bridgeport, with a population of less than a thousand people, is the seat of government for Mono County and provides services for the area's residents and for travelers along the east side of the Sierra Nevada. Nearly all of the flat floor of Bridgeport Valley is privately owned, while the Bodie Hills are predominantly under the supervision of the U.S. Bureau of Land Management.

The major highways in the area are U.S. Highway 395 and State Highway 182; the latter begins in Bridgeport and goes north into Nevada. A paved county road goes southwest from Bridgeport to the crestal area of the Sierra Nevada where it ends. There are many unpaved roads in the Bodie Hills, most of which are passable only to four-wheel-drive vehicles. One exception is the Aurora Canyon road, northeast of Bridgeport. Unpaved roads lead directly to Travertine Hot Springs and The Hot Springs.

In regard to development of geothermal resources, the two most important environmental considerations are the disposal of waste fluids from geothermal wells and the effects of new residential and commercial development spurred by use of the resources. Because of



Approximate area shown in Figure 50.

FIGURE 49 — Approximate outline (dashed line) of known, significant geothermal activity. Map scale is 1:62,500.

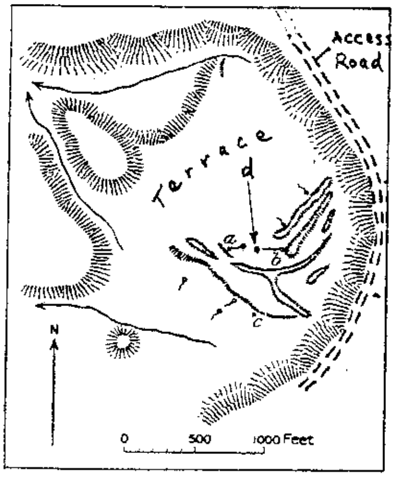


FIGURE 50 — Detail of Travertine Hot Springs area.

a – Hottest spring
b – Second hottest spring
c – Quarry
d – Possible drilling site

the undesirable consequences generally associated with disposal of geothermal waste fluids on the ground surface, it would probably be necessary to inject the fluids into the ground, assuring that they do not affect either the level of the water table or the water quality of the area. If use of the geothermal resources stimulated growth of both the population and economy here, the city of Bridgeport might not be able to, or even desire to, provide services for such growth.

Geologically, there are certain risks in this area because of its seismic activity. For example, a severe earthquake could cause ground failures that might sever or impair production wells or pipelines that supply geothermal fluids. The earthquake could also cause disruption and/or alteration of ground water movement such that the fracture or aquifer that supplies fluid to the well or wells might be sealed off or suffer a reduction in transmissivity. These problems should not preclude geothermal development, but they should be considered in the design and operation of the system.

The distance of transport of geothermal fluids from Travertine Hot Springs or The Hot Springs to Bridgeport should not be a problem as it is only about 3 km maximum. Loss of heat from the fluid would be minimal over this distance if the pipes are insulated. Because of the high content of dissolved solids in the fluid, there may be some problem with scaling in the pipes and wells caused by deposition of $CaCO_3$ or others minerals.

The California Department of Transportation is planning to construct a highway maintenance station approximately in the center of the SE 1/4, section 33, T 5N, R 25E. They have proposed to heat the station with geothermal water if a sufficient supply of fluid can be developed.

CONCLUSIONS AND RECOMMENDATIONS

The westernmost part of the Bodie Hills, just southeast of Bridgeport, is underlain by a geothermal resource, the temperature of which may on the order of 110°C. Various data, including the disappointingly low temperatures encountered in the Bridgeport 1 well, indicate that the reservoir is complex and may be characterized more by movement of fluids strictly along faults rather than by a regular distribution of thermal aquifers, such as in a sedimentary basin. The western boundary of the reservoir may be sharp (impermeable fault contact) or it may be gradational (a mixture of the thermal waters and the cold aquifers of the valley, such that the thermal waters are cooled). The thermal waters probably derive their heat from either rock conduction by circulation to great depths or from a cooling body of magma. Chemical constituents of the waters suggest that the latter possibility should be studied further.

Suggested future study of the area southeast of Bridgeport should include more detailed geologic mapping, resistivity surveys for detection of highly-mineralized fluids, and ultimately, drilling. Because it exhibits the hottest surface temperatures in the area and because no drilling has been done there, Travertine Hot Springs deserves at least one exploratory hole. A suggested site for drilling is shown in Figure 50. The site is favorable because it is flat, is accessible by a dirt road, and has the hottest springs in the entire study area. A drawback is that the terrace is mushy because of numerous seeps.

The temperature of this reservoir is more than adequate for many practical applications in Bridgeport and vicinity. Heating of buildings appears to be the most desirable application because it would least alter the present character of the town and could substantially reduce the present cost of importing heating oil. Winters and even summer evenings here are very cold, thus it would be beneficial to have a local supply of heat. The most serious problem is that there may be an inadequate supply of thermal fluid to meet the needs of the community. The rate of flow at Travertine Hot Springs is only about 50 liters/minute, which is too small for municipal use. Drilling of several wells may increase the supply of fluid, however.

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STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF CONSERVATION

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UNDER CONTRACT DE-AS07-78ID01739

ANNUAL TECHNICAL REPORT
FISCAL YEAR 1978-1979
PLATE 1

GEOTHERMAL AREAS OF CALIFORNIA
LOW AND MODERATE TEMPERATURE RESOURCE MAP

BY C. T. HIGGINS AND R. C. MARTIN
SCALE 1 : 750,000

GEOTHERMAL RESOURCE AREAS - ZONES OF KNOWN ABNORMALLY HIGH GROUND WATER TEMPERATURE (GREATER THAN 20°C OR 10°C ABOVE MEAN ANNUAL AIR TEMPERATURE). (SUPERCEDED BY DATA COMPILED FOR MAP "GEOTHERMAL RESOURCES OF CALIFORNIA")

BOUNDARY BETWEEN MAJOR STRUCTURAL GEOTHERMAL PROVINCES.

● PREVIOUSLY UNRECORDED THERMAL WELLS AND SPRINGS FOUND IN THIS STUDY (JUNE 1978 - MARCH 1979).

◇ THERMAL SPRING.
⊙ THERMAL WELL.
AREAS OF PROVEN OR SUSPECTED THERMAL WATER.

DATA COMPILED FOR "GEOTHERMAL RESOURCES OF CALIFORNIA" MAP NO. 1 (1980)

FAULTS, THERMAL WELLS, AND THERMAL SPRINGS IN MONO BASIN

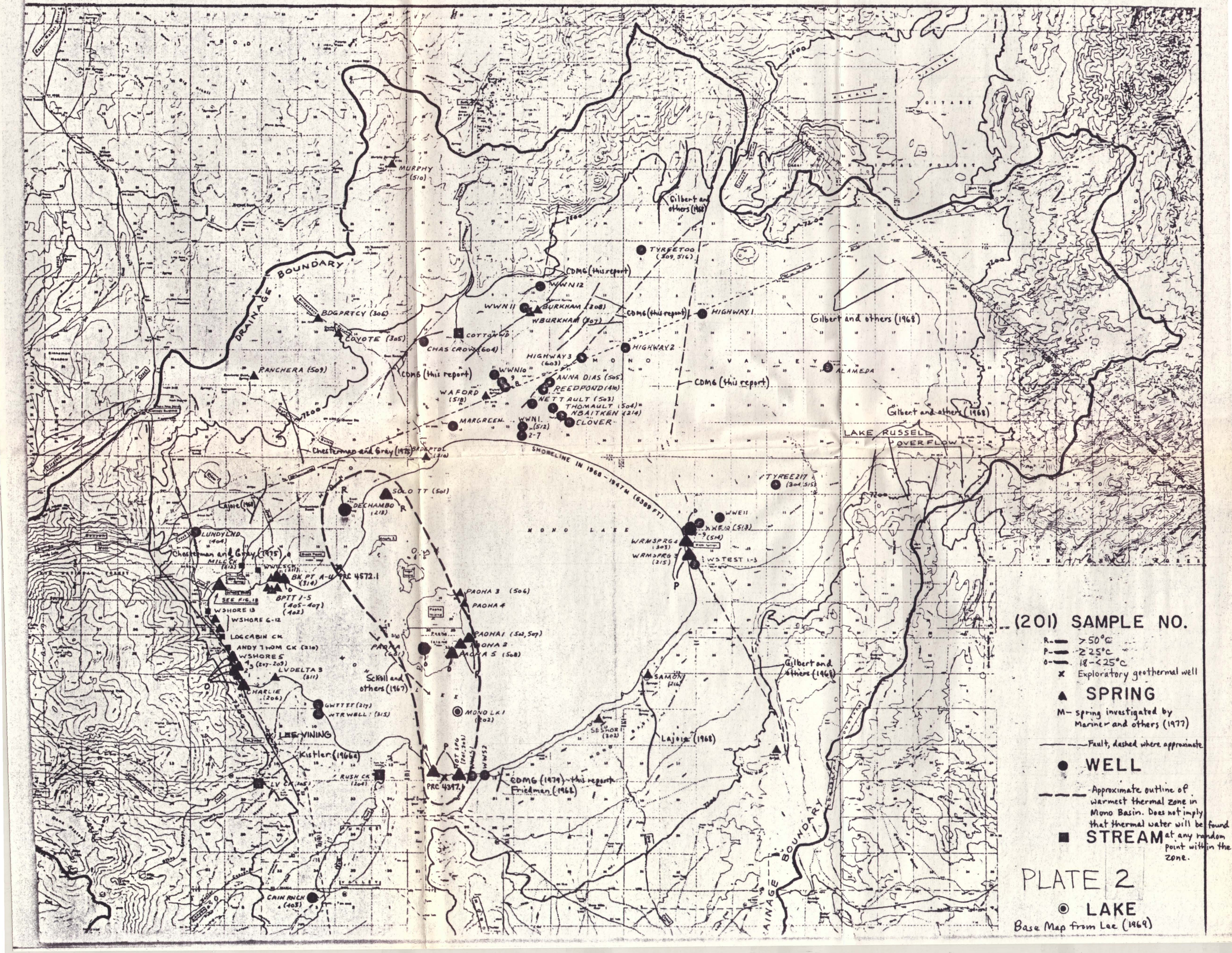


PLATE 2

Base Map from Lee (1969)

EXPLANATION

FAULT

Solid line where existence is certain, dashed where inferred, dotted where concealed by Holocene alluvium; U, upthrown side; D, downthrown side; single arrow and number indicate dip of fault plane; double arrows indicate sense of lateral slip.

FAULT ZONE

FAULT INFERRED FROM PHOTOGRAPHIC EVIDENCE

FAULT INFERRED FROM GEOPHYSICAL EVIDENCE
See plate 2 for magnetic, gravity and seismic data used for inference.

FAULT UNDERLYING SAN DIEGO BAY AND OFFSHORE AREA
(Modified from Moore and Kennedy in press).

SYNCLINE

ANTICLINE

㊶
LOCATION OF TEXT FIGURE

T/h
AGE OF FAULT MOVEMENT

Capital letter indicates age of strata known to be faulted, lower case letter indicates age of strata known to be unfaulted. (See key below and text discussion of ages of strata faulted and not faulted).

Key to age of fault movement symbols

Strata and age	Faulted	Not faulted
HOLOCENE (Soil, alluvium, slopewash)	H	h
LATE PLEISTOCENE (Bay Point Formation)	L	l
EARLY PLEISTOCENE (Lindavista Formation)	Q	q
TERTIARY OR OLDER STRATA (San Diego Formation, Otay Formation, Poway Group, La Jolla Group, Rosario Group)	T	t

PLATE 3

MAP SHOWING CHARACTER AND RECENCY OF FAULTING IN THE SAN DIEGO AREA, CALIFORNIA

After Kennedy and Siang Tan, 1975

Minimum Temp (°C) At Depth Determined From Na, K & Ca Ratios In Well Water

After Herbert, 1977 (SDSU Senior thesis)

PLATE 4

Base from U.S. Geological Survey
1:250,000 Walker Lake, 1969

PLATE 5

LEGEND ON ACCOMPANYING SHEET.

MAGNETIC CONTOURING SUPERIMPOSED ON GEOLOGIC MAP OF REGION

After Kleinhampl and others (1975)

SCALE 1:125 000 Approximately

DESCRIPTION OF MAP UNITS (Accompanies PLATE 5)

Qs	UNCONSOLIDATED SEDIMENTARY DEPOSITS (Pleistocene and Holocene) – Include windblown sand, volcanic ash, alluvium, fan deposits, talus, colluvium, glacial deposits south of Bridgeport and in Bridgeport Canyon, Bodie Hills, and lake beds exposed on Paoha Island in Mono Lake and around the periphery of Mono Lake
Tys	YOUNGER SEDIMENTARY ROCKS (Pliocene) – Fluviatile and lacustrine sedimentary rocks. Include fine to coarse clastic and diatomaceous material; tuffaceous debris common. Age 3-4 m.y.
Tos	OLDER SEDIMENTARY ROCKS (Miocene) – Fluviatile and lacustrine deposits, partly tuffaceous. Include diatomite, fine to coarse clastic beds, and minor ash layers and volcanic breccias. Age about 9-12 m.y.; at least partly correlative with the Aldrich Station, Coal Valley, and Morgan Ranch Formations of Axelrod (1956)

MISCELLANEOUS RHYOLITIC TO BASALTIC ROCKS (Pliocene, Pleistocene, and Holocene)

Qrd	Rhyolitic to dacitic rocks in Mono Lake. Cones, plugs, and flows forming all or parts of the islands in Mono Lake, including Paoha and Negit Islands (Lajoie and Carmichael, 1967, who stated that volcanoes were active during post-Tioga time)
Qb	Andesitic and basaltic rocks in three volcanoes – Aurora Crater, Mud Spring, and Black Point. The oldest volcano is probably Aurora Crater–lava from there was dated at 250,000 years old. Material from Black Point volcano is about 13,000 years old (Gilbert and others, 1968, p. 298)
QTb	Andesitic and basaltic rocks, mainly near Aurora. Related to volcanoes of Pleistocene age; Beauty Peak volcano, 2.8 m.y. old; Mount Hicks volcano, 1.6 m.y. old

VOLCANIC ROCKS EAST AND NORTHEAST OF MONO LAKE (Pliocene)

Ta	Andesitic and basaltic andesite rocks of Cedar Hill and Trench Canyon. Age 2.2-3.6 m.y. (Al-Rawi, 1970)
Tb	Alkali(?)-olivine basalt and basaltic rocks. Age clustered in the range from 2.6 to 4.5 m.y.
Tyr	YOUNGER RHYOLITE (Miocene and Pliocene) – Porphyritic and nonporphyritic rhyolite and rhyodacite. Includes plugs (Spring Peak?), cumulo domes (Bald Peak), dikes, and flows. Ages vary. Rhyolite intruding altered andesite at Aurora is 2.5 m.y. old; rhyolite at Mount Hicks, 3.6 m.y. old (Gilbert and others, 1968); rhyolite and rhyodacite at Warm Spring Flat, 5.3 m.y. old; rhyolite near Mount Biedeman, 9.4 m.y. (Gilbert and others, 1968) and 9.1 m.y. old; rhyolite north of Aurora, 11 m.y.; and rhyolite at Baghdad Peak, 10 m.y. Rocks of intermediate age probably occur
Tvb	VOLCANIC ROCKS OF THE BODIE AREA (Miocene) – Dominantly andesitic and dacitic tuff breccia, lava, and minor tuff, all in blanketlike deposits. Plugs of similar composition are shown by red overprint. Some basalts are included. Include the Rancheria Tuff Breccia, Mount Biedeman Formation, Silver Hill Volcanic Series, Potato Peak Formation, Murphy Spring Tuff Breccia, and Willow Springs Formation, all of Chesterman and Gray (1966) and Chesterman (1968). Most rhyolites in these units are shown with a separate pattern (Tyr). Ages determined range from 7.8 to 13.3 m.y.
Tt	ASH-FLOW TUFFS (Miocene) – Mildly to intensely welded; locally nonwelded. Include conspicuous black to very dark brown vitric zones and, in Bodie Canyon, some tuffaceous sedimentary rocks. Trachyandesitic in composition north of Mono Lake but commonly referred to as latite ignimbrite by workers in the region. Average age is 9.4 m.y., except east of Mono Lake, where age is between 11 and 12 m.y. and where rocks have a different source. Include undifferentiated pyroclastic rocks west of the East Walker River in the Sweetwater Mountains, some of which correlate with the ash flows in the Bodie Hills
Tim	INTERMEDIATE INTRUSIVE BODIES OF THE MASONIC MOUNTAIN AREA (Miocene) – Predominantly andesitic rocks, including minor amounts of rhyodacitic and basaltic rocks as intrusive bodies in the vicinity of Masonic Mountain. At least one body is overlain by the ash-flow tuff unit (Tt) that is about 9.4 m.y. old. Other bodies intrude volcanic rocks of the Bodie area (Tvb) and are overlain by younger volcanic rocks south of Masonic Mountain. Intrusive rocks originally mapped by Johnson (1951), Stanford University (unpub. data), and Al-Rawi (1970, pl. 1, p. 63-64) are included

OLDER VOLCANIC ROCKS (Oligocene and Miocene)

Tpu	Undifferentiated volcanic rocks and andesites in the vicinity of Masonic and northwest of the Bodie Hills in the Sweetwater Mountains. Include volcanics in Masonic Gulch (Johnson, 1951)
Tpmv	Rhyodacite to andesite flows and tuffs, primarily in areas north of Aurora Crater. Include coarse andesite porphyry plug and associated rhyolite and andesite porphyry flows 11 m.y. old in the western part of the Brawley Peaks and in Bodie Canyon, southwest of Aurora. Also includes rocks in Red Wash, near Masonic, described by Johnson (1951), Miocene volcanic rocks of Koenig (1963) in the Sweetwater Mountains, and the andesitic rocks of Moore (1969) in the Pine Grove Hills
Toa	Older andesitic rocks, porphyritic to nonporphyritic. Flows, breccias, and intrusive rocks. Minor tuff and andesitic sandstone and gravel within the unit in Bodie Canyon are not differentiated on the map. Age 13.5-15.4 m.y. in vicinity of Aurora (Silberman and McKee, 1972, p. 14)

In general, all these rocks are weakly altered (propylitized) or, in some areas, intensely altered (argillized and silicified) like those at Aurora and vicinity, Masonic and vicinity, and the Paramount mine area

Tor	OLDER RHYOLITE (Oligocene and Miocene) – Rhyolitic rocks, commonly ash flows and tuffs. Rhyolites in the vicinity of Sweetwater Flat (northwest part of map) were shown as Pliocene by Koenig (1963) but are tentatively correlated with rhyolitic rocks several miles north of the map area in the Pine Grove Hills that range in age from 22 to 28 m.y. (Eastwood, 1969, p. 63, 75). Similar ages were obtained for minor rhyolitic ash flows at or near the base of the Tertiary section east of Mono Lake (Gilbert and others, 1968, p. 280-283)

RED AREAS

PLUTONIC ROCKS (pre-Tertiary)

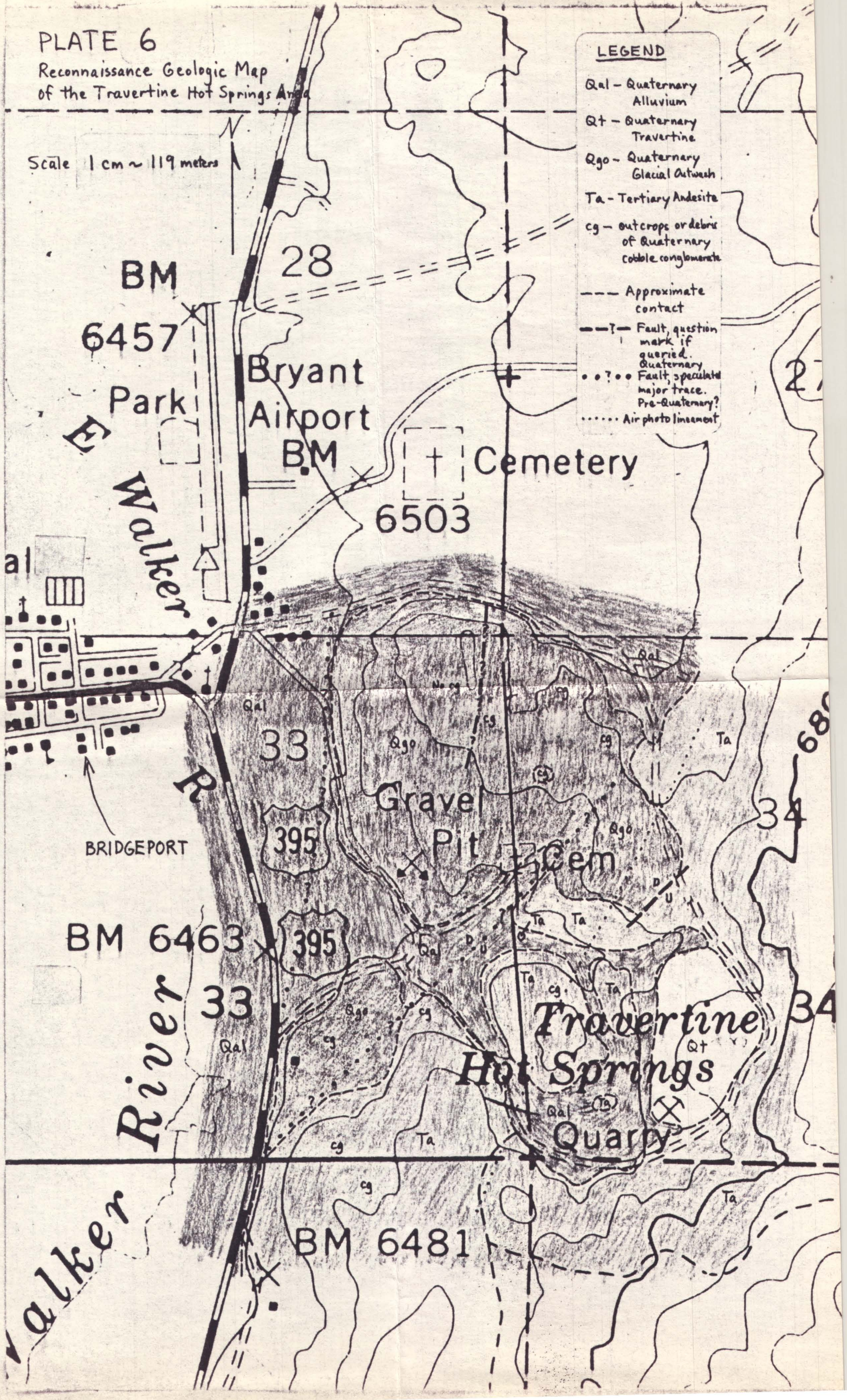
[illegible]	Granitic rocks, equigranular to porphyritic; 93 m.y. old in Bodie Hills at Conway Summit according to Chesterman (1968); 90 m.y. old north of Lundy Canyon; 75 m.y. old in the southern Wassuk Range (Evernden and Kistler, 1970, pl. 2)
pTd	Diorite and related rocks

METAMORPHIC AND SEDIMENTARY ROCKS (pre-Tertiary)

pTms	Chiefly siliceous strata including chert, quartzite, phyllite, and hornfels; some marble in the Sierra Nevada
pTmv	Chiefly metavolcanic rocks, including rhyolite and andesite as flows, dikes, and pyroclastic deposits
pTmu	Metamorphic and sedimentary rocks, undifferentiated
pTmsv	Metasedimentary and metavolcanic rocks, undifferentiated
pTma	Meta-andesite, including pyroclastic deposits, mainly in the Sierra Nevada
pTmr	Metarhyolite, including pyroclastic deposits, mainly in the Sierra Nevada
▒	AREA OF SMALL INTRUSIVE BODIES – Includes plugs of vent areas and domes; excludes rhyolite bodies. Most rhyolite bodies form plugs, cumulo domes, and, less commonly, dikes and are shown separately on the map. Note that intrusive bodies of Tertiary age are not identified in the large area in Nevada where field mapping has not been sufficiently detailed for their determination (see figure 3 in text)
✳	CINDER CONE – Related to alkali(?)-olivine basalt and basaltic rocks in age range 2.6-4.5 m.y.
br ●	BRECCIA PIPE – Mapped only northeast of Mono Lake
☐	ALTERED AREA – Argillic to silicic rocks; propylitic and and pyritic areas not shown. Note that altered areas are not shown for the Sierra Nevada Sweetwater Mountains, Pine Grove Hills, Wassuk Range, Excelsior Mountains, Anchorite Hills, and that part of the Bodie Hills northwest, north, northeast, and east of Masonic
—	Contact, approximately located or inferred – Dotted where concealed; queried where uncertain. Many of the contacts in Mineral County, Nev., particularly in the Wassuk Range and Excelsior Mountains (taken from Ross, 1961, pl. 2) should in all probability be considered approximately located, although for convenience they are shown as solid lines
—	Fault – Dashed where probable; dotted where concealed; queried where uncertain. Bar and ball on downthrown side. Arrows show relative horizontal movement
▲17 ▲10	Potassium-argon sample locality
⚒ ⚒	Group of mines
	Magnetic contours – Showing total intensity magnetic field of the earth, in gammas, relative to arbitrary datum. Hachured to indicate closed areas of lower magnetic intensity. Contour interval 20 and 100 gammas
2466×	Location of measured maximum or minimum intensity within closed high or closed low
— —	Flight path – Showing location and spacing of data

PLATE 6

Reconnaissance Geologic Map of the Travertine Hot Springs Area



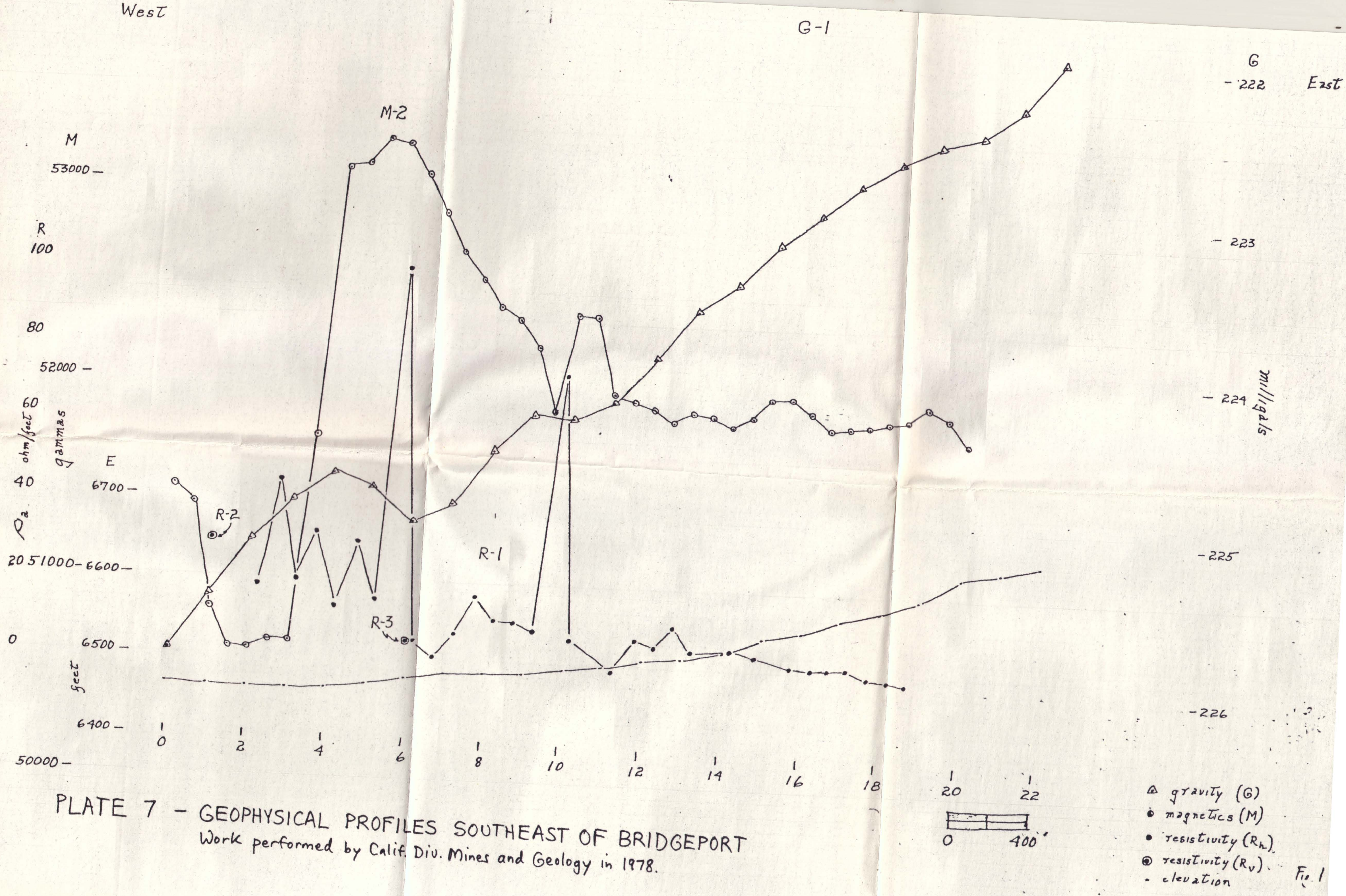


PLATE 7 - GEOPHYSICAL PROFILES SOUTHEAST OF BRIDGEPORT

Work performed by Calif. Div. Mines and Geology in 1978.

Fig. 1

S

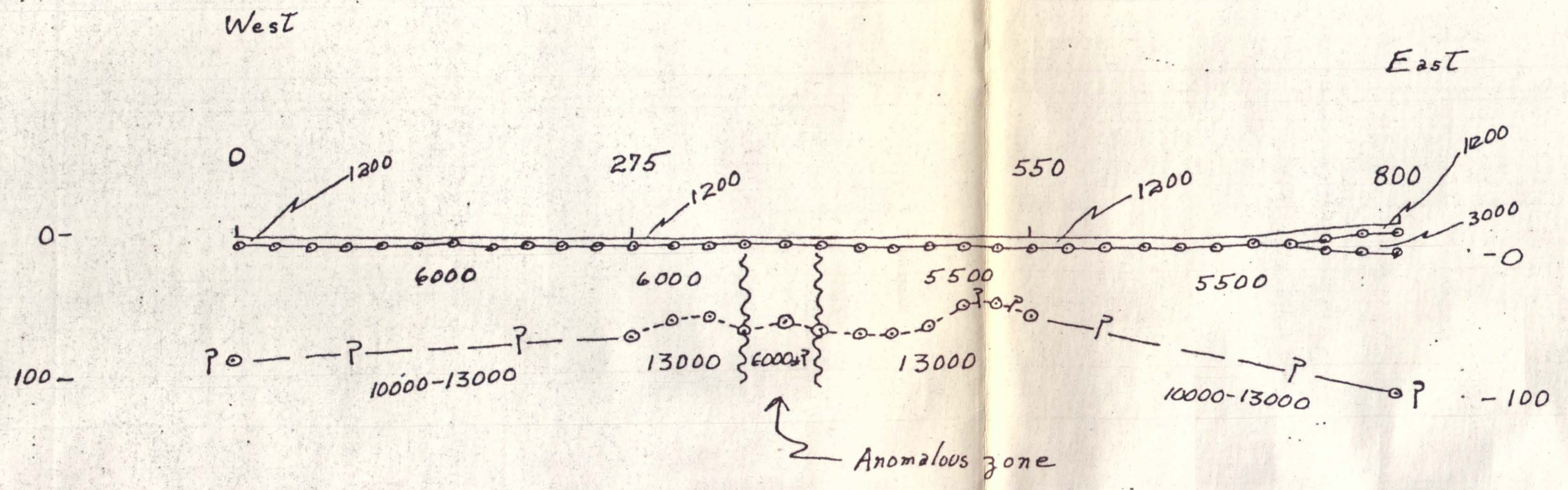
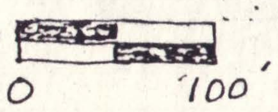


PLATE 8 - SEISMIC PROFILE IN TRAVERTINE HOT SPRINGS AREA

Work performed by Calif. Div. Mines and Geology in 1978.



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6000 - Velocity feet per second (fps)

⊙ - Depth point

—— - Surface elevation (estimated)

Fig.

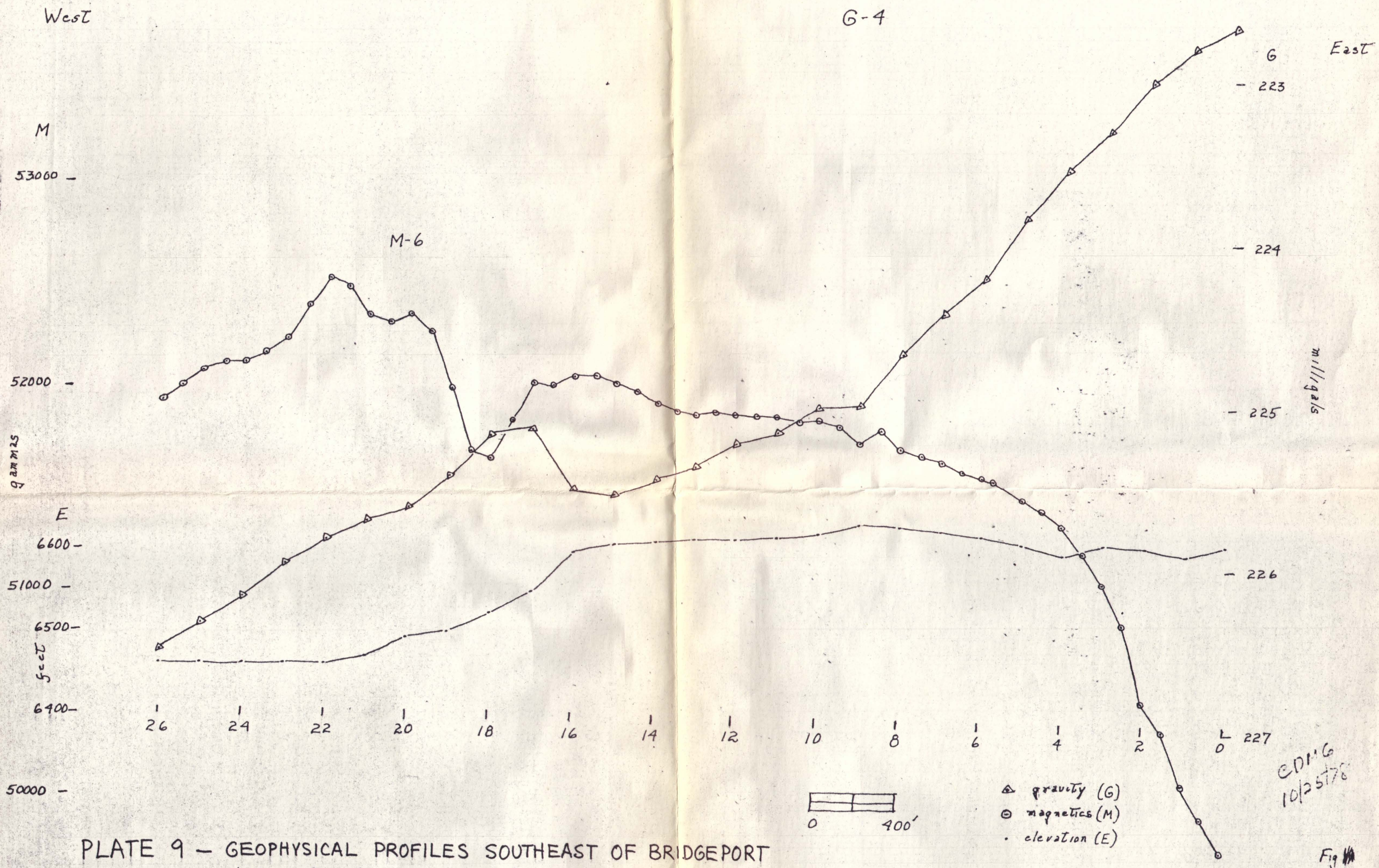

PLATE 9 – GEOPHYSICAL PROFILES SOUTHEAST OF BRIDGEPORT
Work performed by Calif. Div. Mines and Geology in 1978.

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