GL02158

Mid-March Progress Report

on

Hydrologic, geologic, and geophysical case study of the Soda Lakes-Upsal Hogback area, Churchill County, Nevada

Christian Smith

March 16, 1979

Copies to H.P. Ross
B. Sibbett
M. Wright
T. Glenn

A shallow but buried hydrothermal system with no surface discharge lies between two centers of late Quaternary basatic eruptions, Soda Lakes and Upsal Hogback, 12 km northwest of Fallon, Nevada, Figure 1. Mr. Franklin Olmsted of the USGS WRD has collected hydrologic and thermal data at the the Soda Lakes-Upsal Hogback area for seven years. He has initiated but cannot complete a detailed hydrologic/heat flow case study of the area and ~~He~~ has offered ESL an opportunity to analyse his data and to complete the case study. The study outline here may be the first of its kind and may generate interest in continued exploration for non-electrical-generation applications of geothermal resources.

ESL should pursue this opportunity for innovative research at an area included in the on-going Industry Coupled Program. The Soda Lakes-Upsal Hogback area is the only area in Northern Nevada under study with a large hydrologic data base.

I worked in the field with Mr. Olmsted and several of his collegues from the USGS during the March 12-15 trip of Carson City and Fallon. This trip produced the following outline for an integrated earth sciences study of the Soda Lakes-Upsal Hogback area. Mr. Olmsted has promised complete access to the data he has collected and partially analysed during the last seven years. They are avaiable at the USGS offices in Carson City and Menlo Park. He welcomes my offer to synthesize his data.

We agreed that the research should follow this outline:

1) Development of a conceptual model of the Soda Lakes-Upsal Hogsback area. Each element of the model will consist of a distinct set of

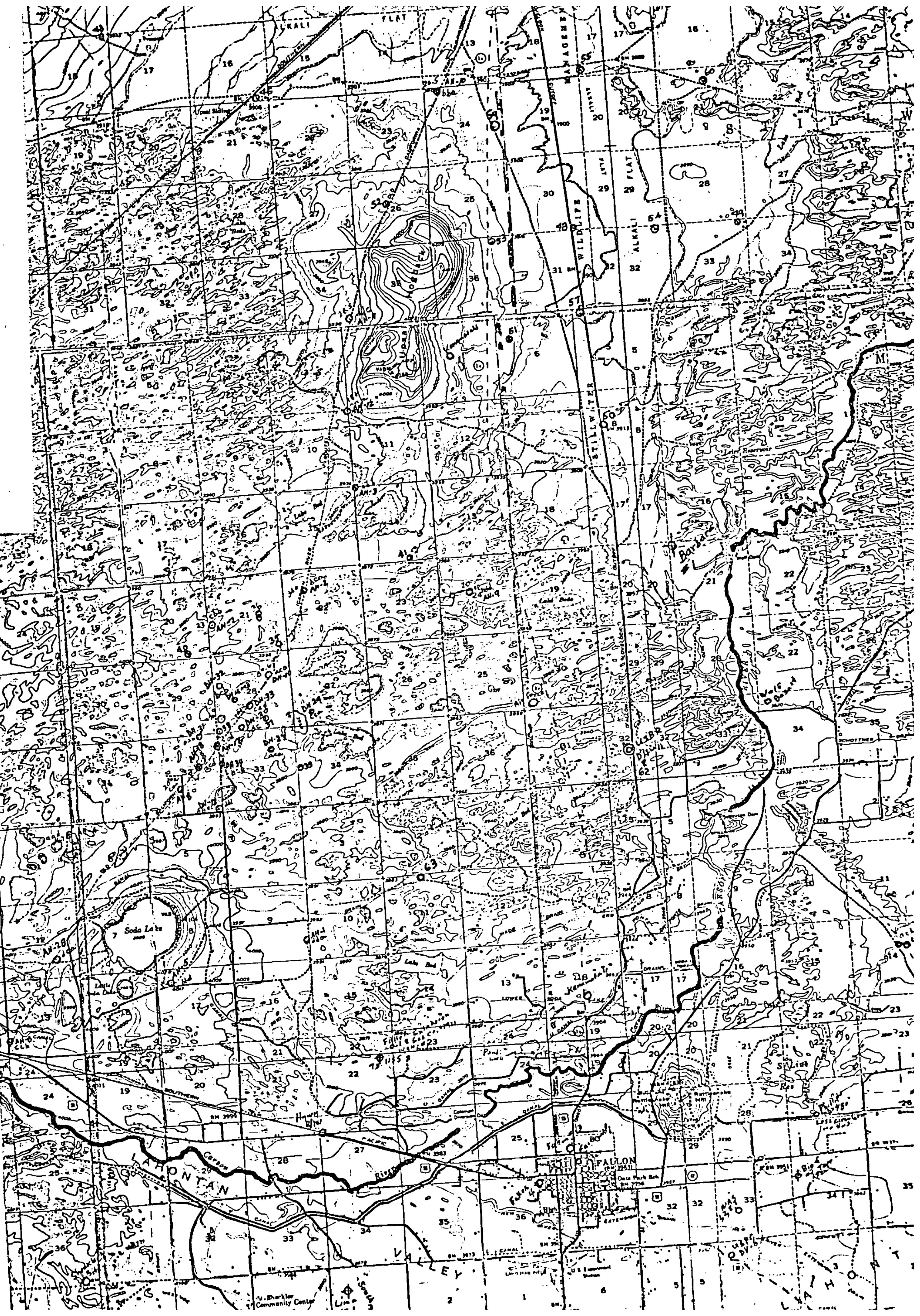

Figure 1 - Soda Lakes - Upsal Hogback area, Churchill County, Nevada showing locations of piezometers sites.

lithologic, hydrologic, and thermal properties.

2) Refinement of the conceptual model. Many shallow wells will be augered or drilled, logged, and pump-tested. The data from these wells will be used to develop a stochastic model amenable to numerical analysis.

3) The numerical model will be calibrated and used to define the heat and mass transport-within a shallow, buried hydrothermal system.

I believe Task 1 is compatible with our Industry Coupled Program case study. It consists of detailing the variations in hydrologic, lithologic, and thermal properties within the area as well as possible <u>from the existing data base</u>. Figure 1 shows the locations of approximately 75 piezometers (~225 wells) in the Soda Lakes - Upsal Hogback area for which the following data have been gathered:

a) Lithologic logs
b) Gamma-Gamma logs
c) Neutron logs
d) Thermal gradient logs
e) Thermal diffusivity calculations
f) Vertical hydraulic conductivity calculations
g) Water Table contours
h) Piezometric surface contours at a depth of 30 m
i) Geochemical analyses

The USGS is continuing to collect these data but are analysing only the geochemistry. Arsenic has been reported in the area. They were interested in my comments on ESL trace element findings.

From the lithologic and bore-hole logs I propose to define the lithologies penetrated by each of these wells. Some are less thatn 10 m deep, others as deep as 500 m; most are 30 or 150 m deep. Once I know the lateral distribution of the various lithologies, I can create a three-dimensional model of the area. Figure 2 shows the variation in lithology seen at a depth of 1 m in one small part of the study area. Morrison (1964) has mapped the regional geology.

The general hydrologic setting in the Soda Lakes - Upsal Hogback area have been presented by Olmsted et al, 1975, Olmsted, 1977, Mifflin, 1968, Glancy and Katzer, 1975, and Rush, 1972. Mr. Patrick Glancy, USGS WRD, Carson City, is finishing a detailed analysis of the three interconnected aquifer systems near Fallon. Mr. Glancy has assured me his cooperation: his hydrologic information will be encorporated into the conceptual model developed in Task 1 and is summarized below.

The driving mechanisms for the groundwater system is thought to be infiltration from releases from the Newlands Irrigation Project and evapotranspiration. The infiltration recharge can be estimated from figures provided by the Truckee-Carson Irrigation District or the USBR. The evapotranspiration discharge is proportional to the density of pheatophytes, particularly the greasewood plant, and the depth to the water table. Mr. Glancy has mapped the phreatophytes in the Soda Lakes - Upsal Hogback area in considerable detail. The data from the 75+ prezometer sites reveal the

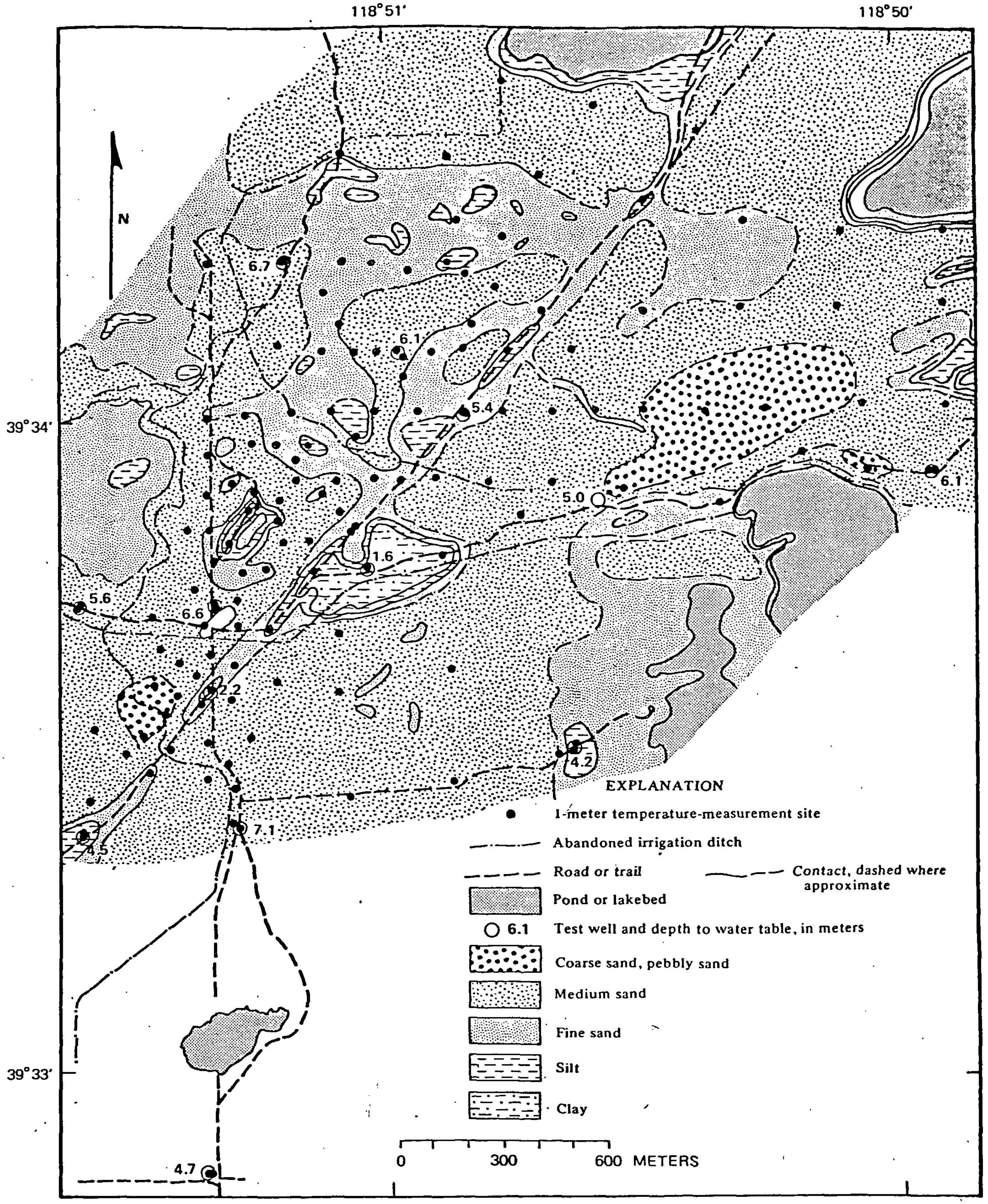

FIGURE ~~4~~ 2.—Soda Lakes area showing character of materials to a depth of 1 m and the depth to the water table in shallow test wells in December 1975.

From Olmsted, 1978

attitude of the water table.

Mr. Olmsted has measured the temperature at a depth of 1 m in all holes drilled in the area. He has analysed his data to estimate the thermal diffusivity of soils at many locations and has determined the mean annual air temperature. These data can be used to determine the conductive heat flow in the area (Lovering and Goode, 1963; Lee, 1977). I propose to include these thermal properties in my conceptual model developed in Task 1.

From these various data the model will be subdivided into several elements, each characterized by a distinct set of lithologic, hydrologic, and thermal properties. This model will make it apparent where there are lapses in the data. Task 2 attempts to bridge these lapses. Task 3 produces a numerical simulation of the heat and mass-transport within the area.

Task 1 uses available data, will require only periodic short trips to Carson City and Menlo Park and a portion of my time, and will produce a detailed three-dimensional model of a shallow but buried hydrothermal system at an area being studies by the Industry Coupled Program.

References available on request.

B. Sibbett

April 4, 1979

MEMORANDUM

TO: H. P. Ross

FROM: W. Frangos

SUBJECT: Initial Review of Soda Lake-Stillwater KGRA Magnetotelluric, Resistivity, and Gravity Data

First-pass examination of magnetotelluric and other geophysical data from the Soda Lake KGRA yields some insight into the structure and configuration of the area. I have also considered the relevance of the various geophysical techniques to the sorts of questions being posed concerning the case study. The magnetotelluric results, in particular, require interpretation beyond that presented by the contractor and by the USGS, since neither adequately recognizes the influence of three-dimensional resistivity configurations on MT data.

The data examined includes:

1) 10 tensor MT sites surveyed by Geotronics Corp. in 1975 for Chevron.
2) 4 tensor MT sites surveyed by Geotronics Corp. in 1977 for Chevron.
3) 60 line-miles of dipole-dipole resistivity (A=2000 ft.) surveyed by McPhar in 1973 for Chevron.
4) a simple-Bouguer gravity map and interpretation by R.R. Wahl dated 1965.
5) 25 tensor MT sites surveyed by Geotronics Corp. for the USGS.

A evaluation of various physical influences upon electrical resistivity with special reference to the Soda Lake-Stillwater environment is included in the Discussion section.

Gravity

Gravity data throughout the Carson Sink and immediate surroundings were gathered, reduced, and interpreted by R.R. Wahl as a student research project at Stanford University. The lack of terrain corrections (for the complete Bouguer reduction) is not of major significance to interpreting the data. Wahl carefully considered rock densities in his two dimensional interpretations, using laboratory determinations on samples as well as known depths to bedrock.

Significant aspects of his interpretation include the discovery of a buried bedrock ridge plunging southwestward from Lone Rock, its highest point, toward Fallon. This feature is apparently a small Basin and Range horst which has been inudated by alluvium from the nearby higher ranges. Alluvium and poorly consolidated sediments on each side of the horst are estimated to obtain thicknesses to 10,000 feet. Wahl interprets a basin floor dipping southward away from Fallon at about 4 degrees; a similar aspect to the west is likely, supporting the general concept of an acurate system of structures roughly concentric with Soda Lake tilting the basin floor down to the southwest.

Galvanic Resistivity

The 2,000-foot dipole-dipole data generally show a resistive over conductive geoelectric structure, the underlying resistivity often being about 2-3 ohm-m. Thickness and intrinsic resistivity of the upper layer are very poorly defined by these results. Several places where the upper layer appears to be missing may only be thinning zones (i.e., "absent" may only mean less than, say, 300 feet thick). No shorter spacing information was gathered to clarify this issue. At no point is there any indication of underlying resistive material.

At one point the contractor's report interprets upper layer resistivity to be about 80 ohm-m. The data appear to me to be poorly suited to such inference, and the MT results generally contradict this conclusion.

Electromagnetic coupling effects for the dipole-dipole array on a two-layered earth can be severe when the upper layer is more resistive than the lower. Using results computed previously (Frangos and Stodt, 1977) I estimate that the apparent resistivities presented by McPhar may be low by as much as a factor of two at the longer separations.

Geologic significance of the thinning of the upper layer is possibly the upwelling of hot, saline waters from a deep reservoir. Figure 1 (reproduced from Olmstead, et al, 1975, Figure 13) presents a hypothetical cross section illustrating a plausible temperature distribution around a fluid flow system postulated for the Stillwater thermal area. Hot, low-viscosity water above the vertical "fault conduit" may cause the shallow regions to be more conductive than otherwise.

Figure 2

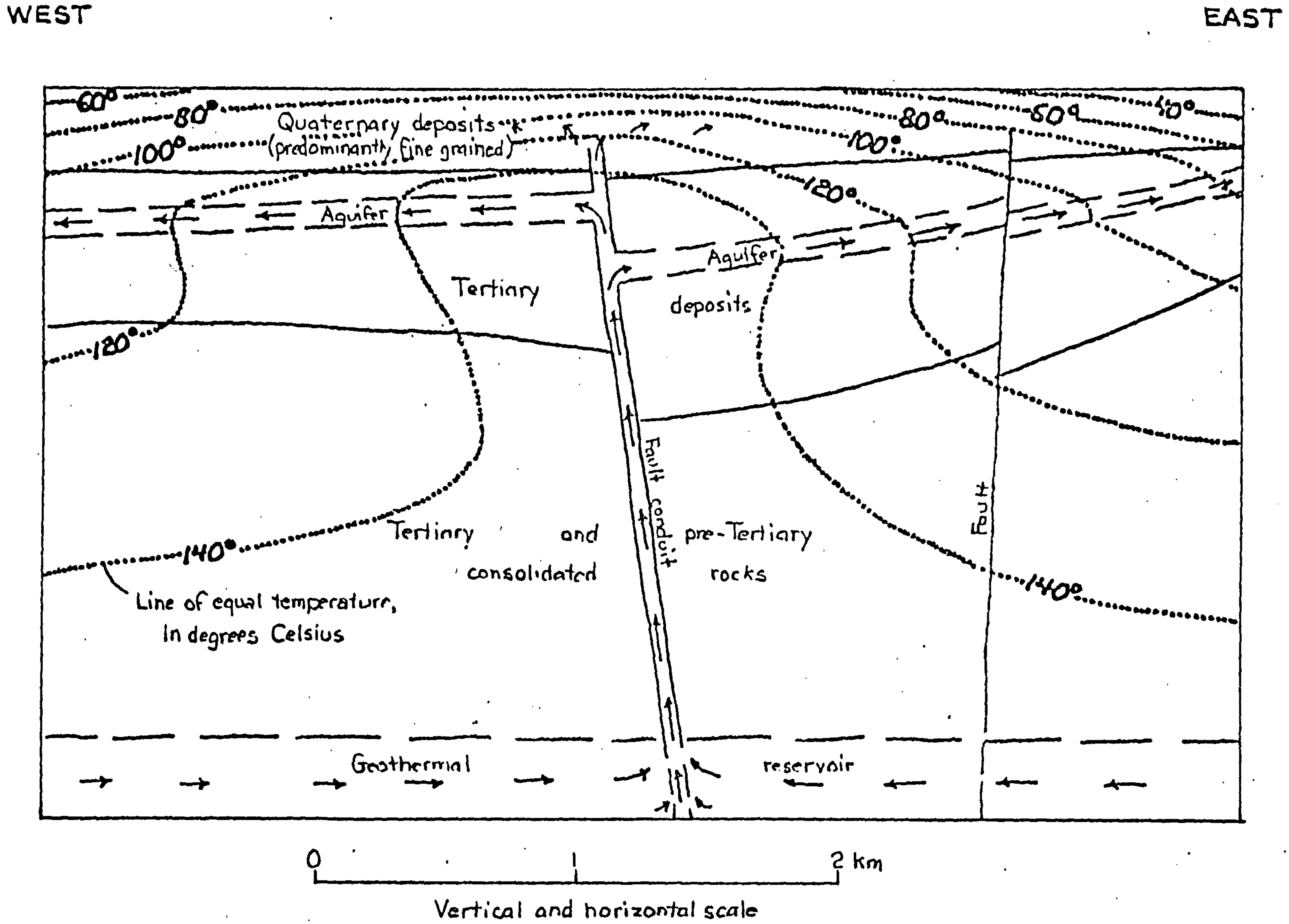

Figure 13.— Idealized cross section of central part of Stillwater thermal anomaly.

A NE-SW alignment of shallow conductive zones is noted by McPhar roughly paralleling the projection of the buried ridge interpreted by Wahl (1965). Thus the Basin and Range structures may be the conduits controlling thermal water flow in this area. An alternative geologic explanation is that the alluvium may have a higher clay content in the depositional centre of the basin than nearer the margins. Such a configuration would cause a lower resistivity upper layer (due to intergranular surface conduction) incidental to geothermal activity.

Magneto-telluric Surveys

Thirty-nine tensor MT soundings have been taken in the Soda Lake - Stillwater KGRA by Geotronics in four different surveys. Data packages and interpretations vary greatly between these surveys, but similar gathering and processing methods are helpful. Three of the four data set have been inverted into discrete layered earth (i.e., one-dimensional) models, one (the 1975 Chevron data) using a parameter estimation technique and the two USGS surveys using a generalized linear inverse method. The only inversion results explicitly available are Chevron's; the USGS presents only grouped, interpreted cross sections. Both the 1975 and 1977 Chevron surveys have been inverted to a continuous resistivity vs. depth function via Bostick's "little inverter."

All of the one-dimensional interpretations have been assembled into pseudo-two dimensional cross sections by simply connecting common points between stations arranged as a profile. As a first-pass procedure, this technique yields plausible and probably useful information. Neither the inferred structures nor the interpreted depths have particular credibility, however, since three-dimensional structures have been shown (Hohmann and Ting, 1978) to cause major deviations from one-dimensional interpretations. Perhaps surprizingly, the scale of lateral inhomogeneities giving rise to unwanted three-dimensional effects is quite large, such that the Soda Lake Region is not adequately one-dimensional below frequencies of about 0.3 Hz.

A remarkably similar geo-electric section is observed on each MT sounding, with only minor deviations. The resistivity sequence from the surface down is moderate, low, moderately high, and very low; typical values determined by discrete-layer one-dimensional inversion methods are 20, 3, 50, and 0.5 ohm-meters, respectively (see Figure 2). Stanley et al (1976, e.g., Fig. 6) tentatively assign the following geologic significances to these inferred layers:

first layer = Aeolian sediments & ashes
second layer = Quaternary playa sediments
third layer = Tertiary volcanic rocks
basement = Tertiary and pre-Tertiary sediments

The apparent basement is then interpreted to be a high-temperature, very saline geothermal reservoir. The first Geotronics interpretative report to Chevron concludes that the deep conductive region is a magma chamber, reasoning that "molten rock is the only material that deep (i.e., 8-10 km) in the earth likely to have such a high conductivity." Both these interpretations are dubious. The shallow regions are generally poorly resolved in these data. Although the instrumental passband permitted analysis up to frequencies of 256 Hz., few data sets yield acceptible coherencies

Inversion Resistivity Range, Ω-m	Inversion Thickness, km	
	Range	Typical
5-20	0-2	$\frac{1}{3}$
1-5	0-2	~1
20-50	2-4	3
< 1	infinite	

Figure 2: Summary of Inversion Results

(i.e., > 0.8) above 70 or 80 Hz and many go no higher than 40 to 50 Hz. Accordingly, the high frequency asymptotes are often poorly defined, requiring arbitrary fixings of parameters in the inverse solutions. Generally, the data meeting the coherency acceptance criterion are numerous but poorly grouped; a great measure of subjectivity is involved in hand-smoothed curves fit by the inversion routines. A notable exception occurs in the 1977 Chevron survey, where acceptible points in the spectral region 0.1 Hz to 10 Hz are extremely rare. The interpretation of resistivities in this region (corresponding to the interval from about a few 100 metres to a kilometre) is very subjective, often without substantial support in the data. Apparently the smoothing procedure is performed assumming that all errors are random since no systematic errors are mentioned and the curves seem to be drawn for best fit without bias. Figure 3 presents a typical suite of Fourier component resistivities passing the coherency criterion and the smoothed sounding curve derived from it. This example is drawn from the 1975 Chevron survey.

The possibility must be raised that the modes have been identified incorrectly on some of the soundings. This may readily be a consequence of three-dimensional resistivity environment wherein the usual terms TE and TM tend to lose their meaning. The TE mode is generally the more conductive and yet a number of soundings show a lower TM resistivity.

After discussion with Phil Wannamaker (University of Utah Geology and Geophysics Department), it seems unlikely that the omnipresent deep conductive zone is either a geothermal reservoir or a magma chamber. Instead, because near-surface three-dimensional inhomogenities tend to cause an upward bias of

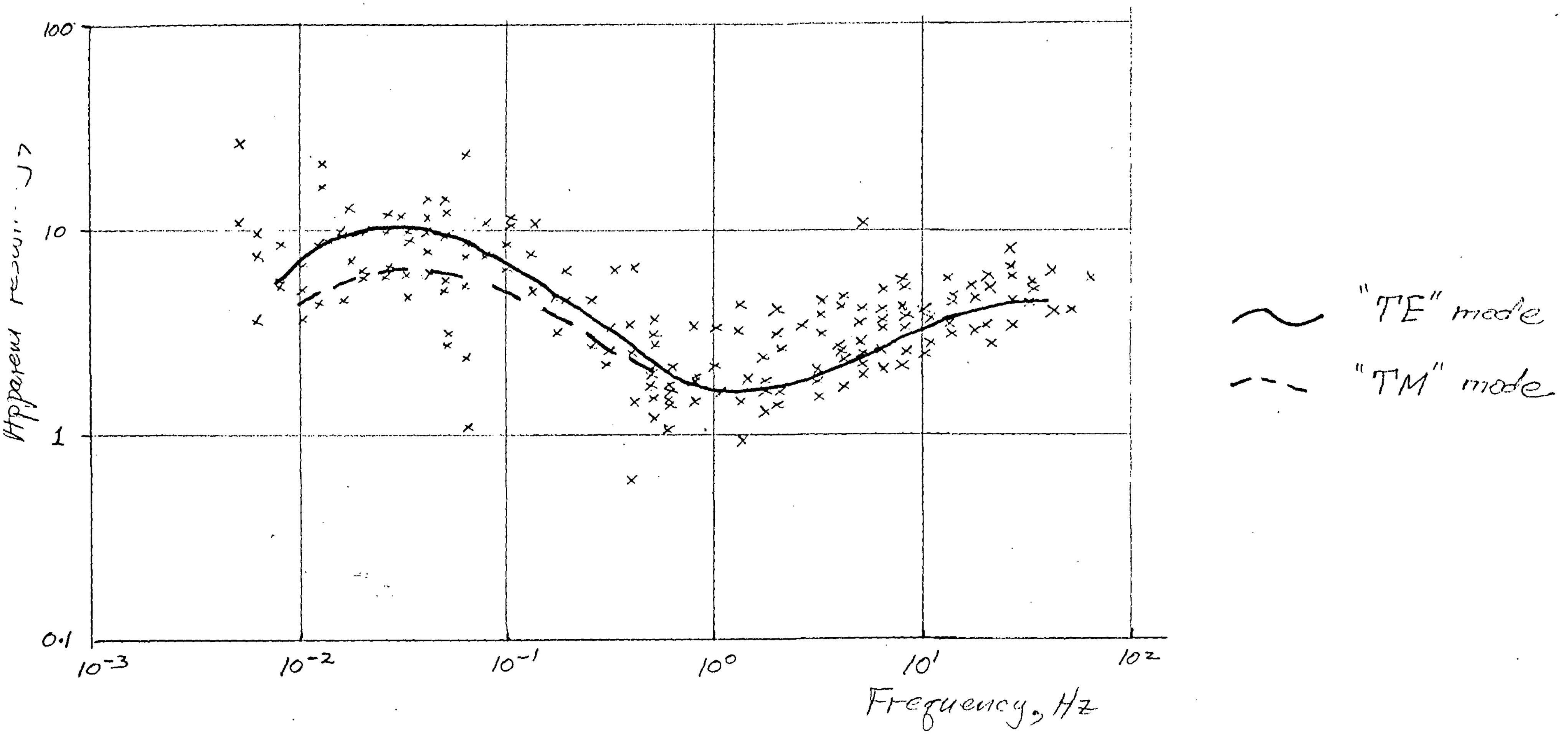

Figure 3:

Typical MT sounding data, showing
hand-smoothed curve through coherent
apparent resistivity values

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interpreted depth, it seems more probable that the very conductive material is the upper mantle. Wannamaker (verbal communication) says that depths estimated by one-dimension fits are frequently shallow by a factor of 2-3 in three-dimensional models he has computed. Such error in these data would be approximately correct for the thickness of the crust in western Nevada (roughly 15-20 km).

One possible indication of a deep heat source might be a conductive portion of the resistive layer. The data were examined for such a feature and no clear evidence for one was found. The problem may be that, since this layer is not thick enough to reach its asymptotic resistivity, we are always dealing with a conductivity-thickness product. MT cannot differentiate between thin portions and conductive portions of resistive layers without asymptotic values.

Discussion

In evaluating electrical surveys of geothermal areas, it is worthwhile to consider the phenomena which effect electrical properties changes in order to understand the significance of any interpretation. In general, electrical methods are employed on the premise that four phenomena associated with geothermal systems all tend to produce anomalously conductive rock in or near the system. These effects are i) heating of pore fluids, ii) increased salinity of pore fluids, iii) increased porosity (or rather, permeability) due to wall-rock alteration, and iv) increased clay content due to wall-rock alteration products. With reference to the Soda Lake-Stillwater KGRA, it appears that pore-fluid heating may be the only significant effect, the latter three being outweighed by other variations within the system. Each effect is briefly examined below with special reference to its applicability in the Soda Lake-Stillwater system.

Saline solutions become more conductive as they are heated largely due to a decrease of viscosity which leads to increased mobilities of the charge-carrying ions. At higher temperatures the effect is reversed since the number of ions available decreases due to ion association. Figure 4, generalized from Quist and Marshall (1969), summarizes this phenomenon for water with a salinity of roughly 700 milligrams/litre. It is readily apparent that a resistivity decrease by a factor between 4 and 10 may be expected due to heating effects alone in the Soda Lake-Stillwater system. Fluid temperature ranges based on drillhole measurements and geochemical inferences might be 20^{o}C to 100^{o}C on the low end or 0^{o}C to 150^{o}C on the high. The shallow conductivity variations mapped by the dipole-dipole survey may thus be due to temperature differences of near-surface groundwater.

Note that for hydrostatic head, i.e., unconfined water such as probably exists here, fluid pressure increases at roughly 100 bars/km, and temperatures of 300-400^{o}C at depths of 2-3 km would result in relatively resistive material. Stanley et al (1976) hint at such temperatures and a linear extrapolation of temperature and gradient observed at the bottoms of holes 1-29 and 44-5 comes near to 300^{o}C at depths of 3 km. This speculative mechanism would provide an explanation for several aspects of the remarkably uniform geoelectric section observed in the MT data over this demonstrably heterogeneous and structurally complex area, in addition to misinterpretation

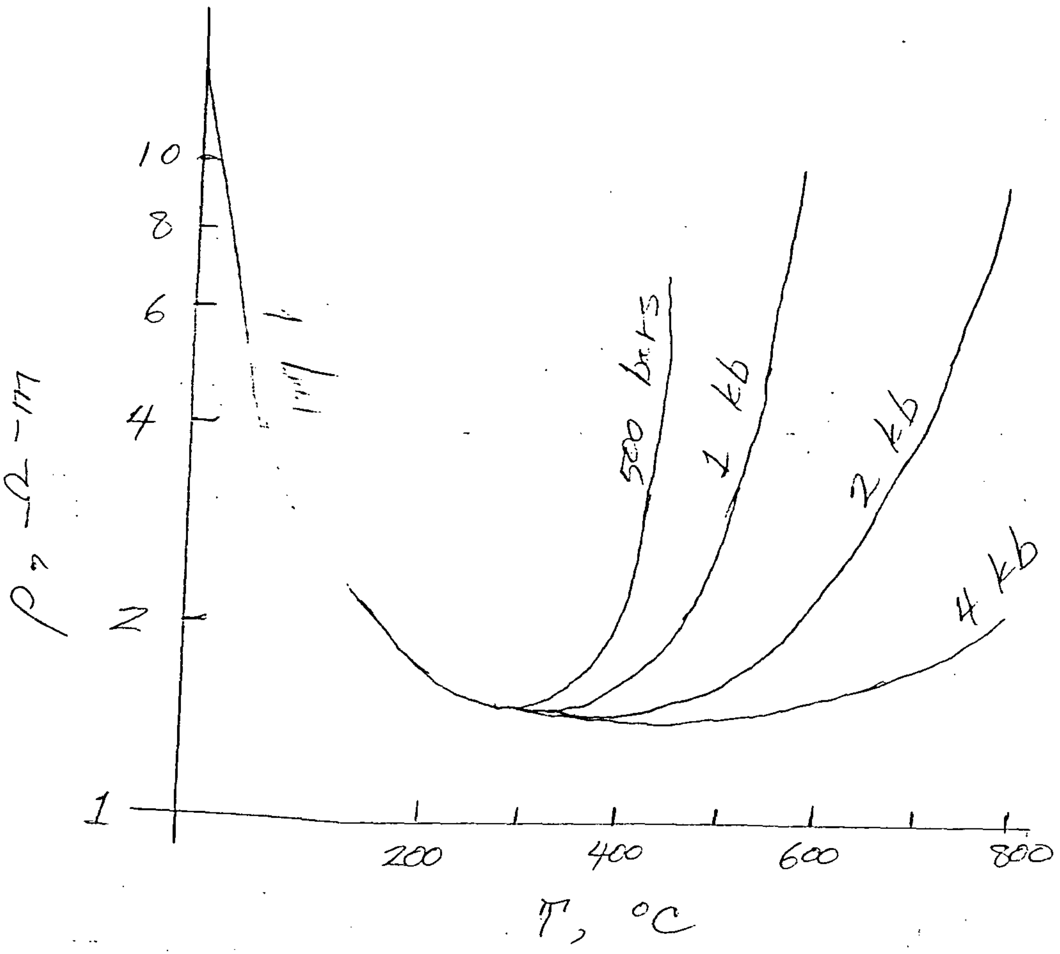

Figure 4

Resistivity of 0.01 M NaCl solution as a function of temperature. After Quist & Marshall, 1969.

due to three-dimensional effects.

Salinity of the pore fluids has a direct influence on their conductivity, since

$$\sigma_{\text{fluid}} = \alpha \sum_i n_i z_i$$

where

N_i = number of ions of ith species present

Z_i = valance of ith species

α = proportionality constant incorporating various physical constants and water properties
the summation is taken over all species present

In many geothermal systems, the hydrothermal fluids are considerably more saline than other nearby fluids. At Soda Lake-Stillwater such may not be the case however. This is the basin for a large region of internal drainage and the remnant of a Pleistocene lake and the groundwaters are naturally quite saline. Soda Lake, for example, has salinites to 61,000 milligrams/litre and well waters are reported in the range 600 to 6,000 mg/l (Olmstead, et al, 1975).

Fresh water influx from surface sources and outflow to the even more saline Carson Sink complicate the situation, making groundwater salinites variable independently of the geothermal waters.

Increased porosity greatly enhances conductivity as expressed in the familiar Archie's Law

$$\sigma_{rock} = \sigma_{water}\,\phi^{m}$$

where

σ = conductivity

ϕ = porosity

m = an empirical parameter dependent upon petrofabric, usually in the range $1 \leq m \leq 2$

In systems of uniform natural porosity, hydrothermal dissolution of rock matrix can produce anomalous conductivity increases through porosity effects alone. Soda Lake-Stillwater rock porosities are innately highly variable. The Tertiary and Quaternary sediments are terrestrial deltaic and lacustrine deposits with a large range of porosities on all geometric scales. Dikes, sills, and intercollated volcanics further complicate the situation. The basement rocks, being largely volcanics, are also predictably inhomogeneous. Thus porosity variations are anticipated to serve poorly as a guide to hydrothermal sources and reservoirs at Soda Lake-Stillwater KGRA.

Clay content is also anticipated to have a poor spatial correlation with hydrothermal activity for reasons similar to those cited for porosity. Clay distribution is predominantly due to sedimentary processes, not hydrothermal ones. Clays increase rock conductivities by allowing surface conduction between ion exchange sites within their lattices. Waxman and Smits (1968) give the following formula for the influence of clays on rock conductivity.

$$\sigma_{rock} = \phi^{m}(\sigma_{water} + BQv)$$

where, in "practical units", $B = 3.83 \left\{1-0.83e^{-1/2\,\sigma_{water}}\right\}$

where

σ, ϕ, & m are as in Archie's Law

and

Q_v = ion exchange capacity of a rock in equivalents per litre of pore volume, dependent upon types of clays present and to the amount of each type

In regions of highly conductive pore waters, the clay content may dominate rock conductivity. Assuming a plausible 1 ohm-m for fluid resistivity at Soda Lake-Stillwater, variations in the second term in the above formula will be twice as important as variations of the first. Waxman and Smits (1968) report Q_v values ranging over a factor of 200 (i.e., from 0.01 to 2.0), which is of the same order as the range of water conductivities. Thus rock resistivities may be expected to be as strongly influenced by irregular sedimentary variations as by thermal effects at the Soda Lake-Stillwater KGRA.

W. Frangos

W. Frangos

WF/smk

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PHILLIPS PETROLEUM COMPANY
DEL MAR, CALIFORNIA 92014
BOX 752 714 755-0131

NATURAL RESOURCES GROUP
Energy Minerals Division
Geothermal Operations

December 28, 1977

Dr. James A. Whelan
Department of Geology & Geophysics
University of Utah
Salt Lake City, Utah 84112

Dear Jim,

Enclosed is the reference list you requested for the Fallon area. Bob Forest, Manager of our Reno Office, has informed me that there is very little published information available.

If you have specific questions about the Fallon region, you might consider calling Bob as he has worked the area for many years.

Very truly yours,

Dick

Richard C. Lenzer
Geologist

RCL/dhk

Enclosure

JAN 10 ENT'D

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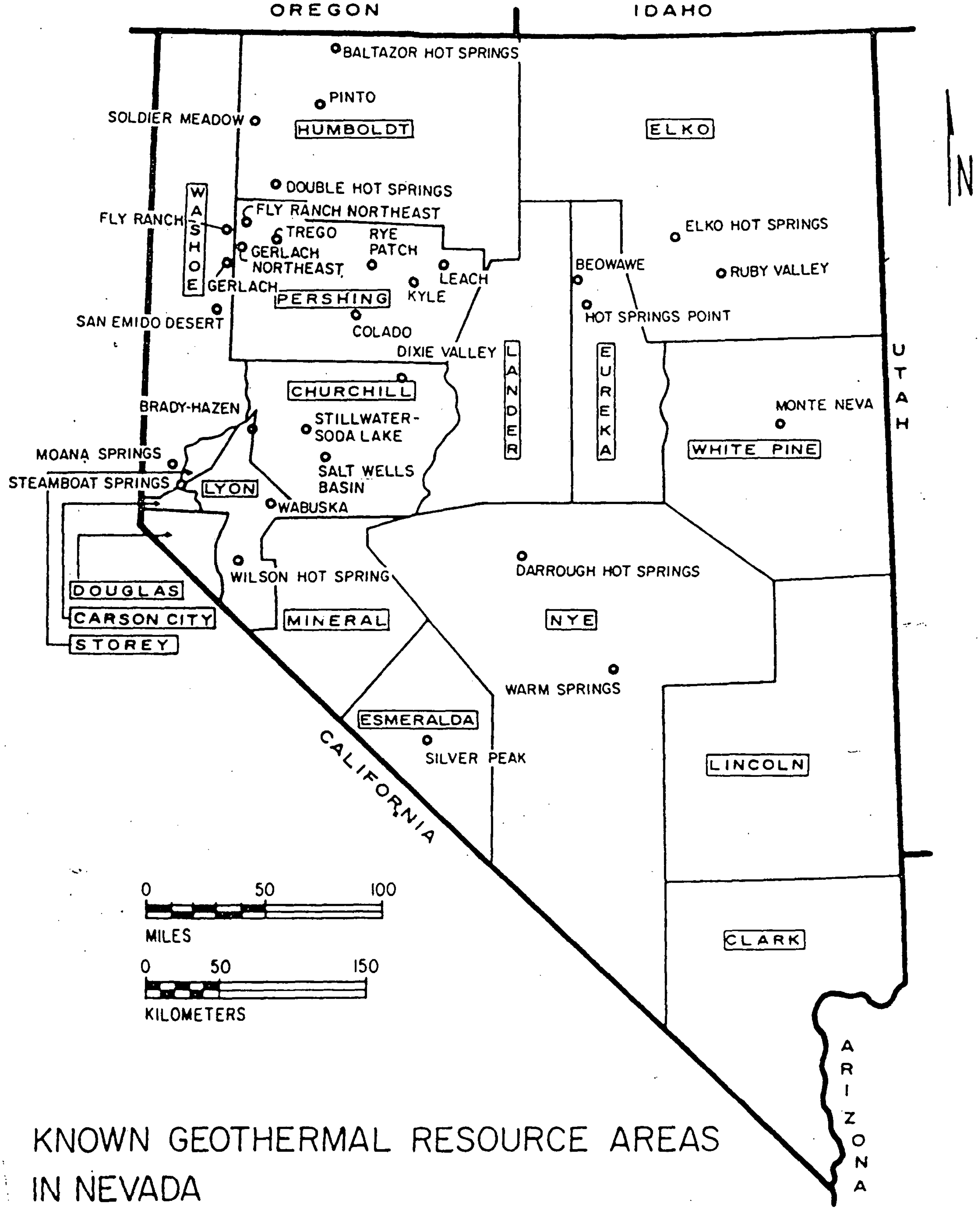

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