GEOHERMAL INVESTIGATIONS of CALIFORNIA SUBMERGED LANDS and SPHERICAL FLOW IN NATURALLY FRACTURED RESERVOIRS

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GEOTHERMAL INVESTIGATIONS OF CALIFORNIA SUBMERGED LANDS
AND
SPHERICAL FLOW IN NATURALLY FRACTURED RESERVOIRS

A Report Prepared Under the Federal Energy
Administration Cooperative Agreement CA 12-50015-0

for the

California Energy Resources Conservation and Development Commission

Prepared Under the Auspices
of

THE STATE LANDS COMMISSION

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INTRODUCTION

A large portion of California State-owned land is the tidal and submerged land along the coastline and around the islands that extends seaward for three geographical miles. Other large areas of State-owned lands form the beds of lakes and navigable rivers. Some evidence, such as the proximity of hot springs, indicates there may be important geothermal potential on these lands. The purpose of this project is to develop methods, tools, and interpretive techniques to explore for and evaluate geothermal resources on submerged lands.

Presently, the state of the art is primitive because there has been little interest or effort in assessing the resource potential of submerged lands, and the limited work carried out thus far has been for scientific purposes. There has been a moderate amount of water temperature measuring for oceanographic or limnologic studies and fairly reliable techniques exist. There have been limited measurements of the temperature, thermal gradient, and heat flow in bottom sediment of the ocean area off California and from the lakes. Probably less than a dozen data points exist for State-owned land. This work was done using large equipment, such as piston corers with outrigger-mounted thermistors arrayed along the core barrels. (Henyey and Lee 1975, 1976). To achieve penetration, such equipment requires heavy weights, strong cable, heavy duty winches, large crews and oceanographic research-type vessels or large barges, and this entails considerable expenses and logistical problems. Clearly, many hundreds, or thousands of data points are required for a remotely reliable evaluation of the resources. The first problem is to assess existing methods and develop others that will enable economical and efficient exploration for geothermal resources on submerged lands.

As a first step, requests for proposals were sent to five groups of individuals active in geothermal studies. Three proposals were received in response to the requests. One proposal represented two of the five groups. Two of the proposals were for the development of towed devices to measure temperature anomalies in the water column. In evaluating these proposals it was recognized that there is very little know-how on extrapolating water column data to conditions below the bottom. In addition, it was known that the water column is very dynamic, subject to internal waves, turbulence, and mixing. It was concluded that it was best to work with the simplest and most direct methods that would allow measuring bottom heat directly and thus avoid, as much as possible, a great mass of ambiguous or difficult to interpret data.

The Lawrence Berkeley Laboratory was awarded a contract by the State Lands Commission in January, 1976. According to their proposal, they would design, construct and test suitable instruments for thermal studies. In addition, an advisory panel of experts from the Laboratory would be established to evaluate techniques, and instrumentation for the assessment of the geothermal potential of submerged State lands in an orderly, scientifically sound and beneficial manner.

The instruments designed for thermal studies would be durable, portable, and operable from a small boat and in water depths to 200 meters. The designed instruments are described in a report by P. W. Wilde and J. Oldson. These instruments consist of a surface control and readout box connected electrically to a subsurface temperature probe. The laboratory also provided computer modeling, calibration tables, and computer conversion of field data to temperature at each of five thermistors, calculation of thermal gradient, and heat flow based on assumed constants.

Following design, construction and testing of the probe, it was delivered to State Lands Division personnel. Differing and improved models were used to collect thermal data from the Salton Sea, Clear Lake and Mono Lake. These were practical field tests to evaluate the instrumentation and techniques while collecting information on the thermal characteristics of these lakes. Although less emphasis was placed on assessing the geothermal potential of the Salton Sea than Clear Lake and Mono Lake because of the limited State-owned land under the Salton Sea bed, it was selected for the initial tests because of the harsh and potentially dangerous weather conditions on Mono Lake and Clear Lake during the late winter and early spring. In addition, there were considerable geothermal data very near the southern margin of the Salton Sea that suggested there are geothermal conditions beneath the lake bed that would make testing in that area worthwhile from an instrumental and data interpretation viewpoint.

At the start of the program adequate data were not available for design of experiments to map bottom anomalies, determine the effects of geothermal anomalies on the water column or even what station spacing or within station procedures are most appropriate. Direct methods would allow collecting at least some of these data. Frequently within station and very local variability or extraneous effects are such that the highest level of instrumental precision and accuracy or elaborate operational procedures are unwarranted.

METHODS FOR GEOTHERMAL RESERVOIR DETECTION
EMPHASIZING SUBMERGED ENVIRONMENTS

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May 21, 1976

Prepared for:
California State Lands Commission

Funded by:
California State Lands Commission

ACKNOWLEDGMENTS

We wish to acknowledge and express gratitude to the many individuals who assisted and advised us during this project.

The advisory board of Professor H. F. Morrison and Professor P. A. Witherspoon of the University of California and Dr. J. Apps from the Lawrence Berkeley Laboratory was a much appreciated source of counsel and recommendation.

Drs. R. F. Corwin and A. Dey of the University of California and H. Wollenberg of the Lawrence Berkeley Laboratory generously spent time reviewing this report, and their suggestions are included.

H. Beyer and R. Clymer of the Engineering Geoscience Department of the University of California assisted with and provided much of the literature used for this report.

We received many helpful suggestions and ideas from C. F. Eaton, R. Martin, and E. Welday of the California State Lands Commission.

This work was supported through Agreement LC 6028 between the State of California and the Lawrence Berkeley Laboratory, U.S. Energy Research Development and Administration. The original funding was through cooperative Agreement No. CA 12-50015-00 between the State of California and the Federal Energy Administration.

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I. ABSTRACT

This report has been prepared for the California State Lands Commission to aid them in evaluating exploration programs for geothermal reservoirs, particularly in submerged land environments.

Three charts, the core of this report, show: 1) a logical progression of specific geologic, geochemical, and geophysical exploration techniques for detecting geothermal reservoirs in various geologic environments with emphasis on submerged lands, 2) various exploration techniques which can be used to develop specific information in geothermal areas, and 3) if various techniques will apply to geothermal exploration according to a detailed geologic classification. A narrative in semi-outline form supplements these charts, providing for each technique; a brief description, advantages, disadvantages, special geologic considerations, and specific references.

The specific geologic situation will control the exploration criterion to be used for reservoir detection. This report establishes general guidelines which may be of use in evaluating such a program, but the optimum approach will vary with each situation.

II. INTRODUCTION

The purpose of this report is to provide a guideline or framework for the detection and assessment of the geothermal reservoir potential for various geologic environments, primarily submerged lands. The core of the report is a group of three charts which compare geologic, geochemical, and geophysical exploration techniques in regard to either certain geologic environments or certain types of information to be developed for geothermal systems.

Specifically, Chart I., containing a detailed classification system with specific examples, lists the various exploration techniques along with brief explanations of their use in conjunction with each geologic situation. Chart II. relates types of information pertinent to a geothermal system with the methods used to develop this information. Chart III. lists a logical progression of exploration techniques to be used for general geologic environments. All three charts emphasize techniques for exploring on submerged lands, either in lake or marine environments.

The narrative, in semi-outline form, is to be used in conjunction with the charts. The classification section of the narrative describes the basis for the classification, and shows how a number of specific geothermal systems may be included. Three sections on techniques briefly describe the specific geologic, geochemical, and geophysical methods; list advantages, disadvantages, and special geologic considerations; and mention specific references for further details.

Figure #1 shows the integrated approach for using the total report. First, the pertinent geologic features of a particular piece of land are noted. The land is classified according to the system on Chart I., and the various applicable exploration techniques are cited. If specific types of information are needed, the suitable techniques are found on Chart II. Then the land is classified according to the more general system of Chart III., and a procedure for investigating the geothermal potential of the property is developed. Details of advantages, disadvantages, and special geologic

considerations for the selected techniques are explained in the narrative. Specific references are given for each technique.

The list of techniques in preferential order is a suggested and logical progression. The criterion for establishing the order includes: 1) the ease of using the technique in the field and the size of the field crew needed, 2) relative expense, 3) effective methods of data interpretation for each technique, 4) correlations between anomalies and geothermal systems, and 5) proven results in geothermal exploration. No single technique will give reliable information by itself - a total exploration approach should be used with methods supplementing each other. A conclusion based on anomalous data from only one method can be misleading. Diverse methods should provide support - for example geochemical water analysis could be used to compliment the electrical sounding data interpretation.

A great deal of research is being performed on all aspects of geothermal power and reservoir detection. Two prime sources of information have been the 1970 and 1975 United Nations Symposium on the Development and Use of Geothermal Resources. Papers from the 1975 Symposium are in the process of being printed and details from some of them, particularly in the geochemical area, have not been included in this report. This report then is an embarkation to establishing a practical guide for geothermal exploration. This effort should be revised and expanded as new information is made available. Some techniques such as self-potential, audiomagnetotellurics, microseismic, and seismic noise offer promise as effective exploration tools, but more work is required in correlating anomalous data with geothermal reservoirs and establishing field techniques. A few techniques such as induced polarization and microseismic are mentioned briefly - in subsequent reports they should be discussed in more detail. This paper is an attempt to coordinate available geothermal exploration literature and proscribe a logical series of procedures for detecting the geothermal potential for given geologic environments, particularly for submerged lands.

III. CHARTS, FIGURES, AND TABLES

- A. Chart I. - Geologic Classification and Geothermal Detection Methods
- B. Chart II. - Geothermal Detection Methods and Information Developed
- C. Chart III. - Geologic Classification and Methods Flow Chart
- D. Figure #1 - Block chart showing procedure for geothermal prospecting on submerged land
- E. Table #1 - Identified hot-water convection systems with indicated subsurface temperatures above 150 degrees C (Renner and others, 1975)
- F. Table #2 - Chemical composition of rivers and lakes (Livingstone, 1963, p.16-17)
- G. Table #3 - Summary of geochemical methods and techniques for analysis
- H. Table #4 - Summary of geophysical methods and techniques

CHART I. - GEOLOGIC CLASSIFICATIONS AND GEOTHERMAL DETECTION METHODS

[illegible]

CHART II. GEOTHERMAL DETECTION METHODS AND INFORMATION DEVELOPED

INFORMATION DEVELOPED CONCERNING:

DETECTION METHODS	RESERVOIR LOCATION	RESERVOIR SIZE	RESERVOIR TEMPERATURE	VAPOR SYSTEM VERSUS HOT WATER SYSTEM	INSULATION (LEAKAGE)	PERMEABILITY OF RESERVOIR AND CAP ROCKS	MISCELLANEOUS
GEOLOGY: REVIEW OF EXISTING INFO.	Review existing information including air photographs, maps, and literature - field mapping of springs, fumaroles, faults, deposits, etc.	Existing information including photographs, maps, and literature may give evidence of size of field.	Literature on deposits, structure, and surface manifestations may be a help in estimating reservoir temperature.	May be difficult by reviewing existing information to tell if system is hot water or vapor.	Existing information may describe surface manifestations and geology which are evidence of leakage.	Current description of rock type and geologic maps should be a good source concerning permeability of cap rocks - reservoir rocks will be difficult.	
GEOLOGY: FIELD WORK AND MAPPING	Field work, mapping, and analysis of surface manifestations, intrusives, extrusives, faults, etc.	Field mapping of surface manifestations, faults, caldera rims, etc. may give evidence of size of field.	Type of surface deposit or rock alteration can be an indication of reservoir temperature.	Field mapping probably will not give information as to type of system.	Obvious leakage should be evident during field work. Possibility of leakage may be determined from study of rock types.	Information concerning permeability of cap rocks should be obtained from field studies.	Field mapping and study of deposits should give helpful information on source and homogeneity of water supply and corrosion potential.
GEOCHEMISTRY: ANALYSIS OF HYDROTHERMAL WATERS	Various geochemical indicators for estimating reservoir locations including SiO_2 , Na/K , Ca , HCO_3 and Hg content of streams, lakes, etc.	Surface extent of geochemical anomalies may be an indicator of size of field.	Analysis of waters for geochemical indicators are some of the most effective methods for estimating reservoir temperature.	High chloride content may indicate a hot water system. Difficult to estimate the vapor system temperature.	Analysis of Cl and Cl/B for evidence of shallow mixing.	Estimations of flow rates may be made by comparing various geochemical and geophysical indicators.	Analysis of S for corrosion. Analysis of Cl and Cl/B for evidence of shallow mixing and homogeneity of water supply - also Cl and carbonates.
GEOCHEMISTRY: ANALYSIS OF GAS	Certain types of gas leakage may be indicative of geothermal reservoir.	Extent of gas leakage may give indication of size of field.	Various gas indicators which can give supporting information on reservoir temperature.	Can be difficult to tell from gas analyses the type of system. May be able to distinguish system type by using ratio of noble gases.	Certain types of gas leakage may be an indication of a potential geothermal system.	Gas leakage will occur most noticeably with permeable cap rocks.	Gas analyses will provide supporting data for water analyses.
GEOCHEMISTRY: ANALYSIS OF DEPOSITS	Surface manifestations of Hg , SiO_2 and CaCO_3 deposits may be a geothermal indicator.	Extent of CaCO_3 , SiO_2 and Hg deposits may show the size of field.	SiO_2 deposits imply high sub-surface temperature, while CaCO_3 deposits imply low sub-surface temperature.	Will be difficult to tell from deposit analyses the type of system.	CaCO_3 or SiO_2 may be deposited by leaking hydrothermal waters. Hg halos may also be found.	Surface flow of waters must be slow for deposits to form.	Deposits can show circulation patterns. Will also give indication of water effects on pipes.
GEOCHEMISTRY: ANALYSIS OF ISOTOPE FRACTIONS AND MISC. ANALYSIS	May not be too useful in determining reservoir location.	Can be used as an indicator of the history of geothermal water (isotope fractions).	Isotope fraction analysis is one of the few methods available to estimate the temperature of a vapor system.	Isotope fraction analysis can give vapor system temperature.	Isotope fractions analysis is a good indicator of the extent of fresh water mixing.	Data can be obtained concerning source of water for reservoir and age of recharging water.	Data can be used as an indicator of the history of geothermal water.
GEOPHYSICAL: SEISMIC (including refraction and reflection)	Primarily a structural method for lateral boundaries, depth to reservoir basement, active fault planes, etc.	This is a good structural method to use for finding lateral boundaries, depth to basement, etc.	Seismic interpretation can possibly supply information on hydrothermal alteration.	Will be of little use in distinguishing between systems.	P wave - delays may indicate if cap rock is silicified.	As a structural method, this could give reliable data concerning faults and fault intersections (paths for water flow).	In some situations this will give a better indication of heat flow characteristics than direct measurements.
GEOPHYSICAL: GRAVITY	This method can be used for detection of hydrothermal alteration and structural features such as faults, calderas, etc.	Can be used for detecting structural features which will limit size of reservoir. May be correlation between magma chamber and regional gravity anomaly.	May detect hydrothermal alteration which can be a temperature indicator.	Will be of little use in distinguishing between systems.	May detect hydrothermal alteration of cap rock.	Will see through ground cover to provide data on structure and rock alteration.	Primarily a structure and rock alteration determining method.
GEOPHYSICAL: MAGNETICS	Primarily a structural method for thickness of sediments over reservoir, possibly hydrothermal alteration, etc. Also useful to determine depth to Curie temp.	Auxiliary structural which may be of some help for depth determination and below surface structure.	May be of some use for detecting hydrothermal alteration which can be a temperature indicator.	Will be of little use in distinguishing between systems.	May detect hydrothermal alteration of cap rock.	Probably of little use in determining permeability of reservoir and cap rocks.	May be useful for determining the thickness of sediments over reservoir.
GEOPHYSICAL: HEAT FLOW (shallow and surface measurements - 30 meters or less)	Fast, relatively inexpensive preliminary surveys can be made. May be interpretation problems. May just measure temperatures at bottom of hole.	May be of some use as a fast preliminary survey method, although may be difficult to interpret.	Because of interpretation problems, may be difficult to estimate reservoir temperature without supporting information.	Because of interpretation problems, may be difficult to use data to distinguish between systems.	Data may show surface and ground cover effects rather than actual insulation properties.	Permeability of reservoir and cap rocks may affect shallow and surface measurements.	Shallow and intermediate surveys should be integrated for most useful application.
GEOPHYSICAL: HEAT FLOW: (intermediate depths - 30 - 200 meters)	More expensive than shallow measurements but more reliable data will be obtained.	Expensive but can provide reliable data for estimating reservoir size.	Direct reliable method for obtaining data on reservoir temperatures. Good information on heat flow and gradient.	Can be direct method to find out type of system.	Reliable thermal gradient and conductivity data should be obtained from this method.	Permeability of reservoir and cap rocks will affect intermediate depth heat flow measurements.	Continual monitoring may give data on total heat flow potential of field.
GEOPHYSICAL: DIRECT CURRENT RESISTIVITY	This method can be used for location, size, and depth of reservoir - good depth penetration.	Can be used to determine size and lateral boundaries. Will provide good depth information.	Possibly can be used for reservoir temperature estimations.	May be of some supporting use in determining type of system.	Leakage may affect rock resistivity.	An important factor in resistivity measurements is the permeability of reservoir and cap rocks.	Bipole-dipole array can be used for a regional survey, with a dipole-dipole array for a detailed follow up.
GEOPHYSICAL: INDUCTION (excluding tellurics and magnetotellurics)	Effective method for shallow resistivities for initial surveys, particularly when heat flow measurements are difficult.	Will work well for shallow lateral boundary determination.	This is an effective method for simple shallow temperature estimations. May work as a substitute for expensive heat flow measurements.	May be of some supporting use in determining type of system.	Shallow changes in resistivity because of leakage should be evident.	Permeability of cap rocks will be an important factor in induction methods.	In some situations this will give a better indication of heat flow characteristics than direct measurements.
GEOPHYSICAL: SELF-POTENTIAL	Field techniques are easily adaptable for work in submerged land environments - may be simplest and most inexpensive.	Can be a simple inexpensive method for gathering data on reservoir size in support of other methods. Good in marine situations.	Direct correlations have not been established between anomalies and reservoir temperatures.	Will be difficult in interpreting data in regard to type of system.	Ascending or descending waters will give rise to streaming potentials - measurable by self-potential.	Over-all patterns of water circulation may affect self-potential measurements.	Direct correlations have not been made between all self-potential anomalies and geothermal systems.
GEOPHYSICAL: TELLURIC and magnetotelluric methods	Effective land techniques for exploration at various depths may be difficult for submerged land surveys.	Effective survey techniques with good depth penetration. May be simple and inexpensive but primarily for land use.	The method emphasizes conductive bodies such as found with hot water and alteration zones. Primarily for land use.	Data will be of use, along with data from other methods in distinguishing type of system.	Leakage and permeability of cap and reservoir rocks will effect telluric measurements as the method measures conductivity of the material, rather than resistivity.		Data at good depths will be obtained by magnetotellurics.
GEOPHYSICAL: REMOTE SENSING	Good airborne methods may present interpretation problems. Useful for initial surveys but for surface information only.	Possibly will be of some use in distinguishing lateral boundaries of system.	Because of lack of depth penetration, may be difficult to use data for temperature estimations.	May help in mapping of surface indicators of system type.	Remote sensing may be the best method for the over-all detection of leakage manifestations.	Most data concerns surface effects only.	This could be an effective method for the total monitoring of a geothermal field.
GEOPHYSICAL: SEISMIC NOISE and microseismic	May be an inexpensive method to delineate structural boundaries. Problems correlating seismic noise and geothermal activity.	May be an inexpensive method to determine structural boundaries of system.	Correlations have not been established between seismic noise and below surface temperature.	When correlations have been established, this could be a good method for determining type of system.	Adequate correlations have not been made between seismic noise and geothermal activity, although leakage may be one source of noise.	P -wave delays may indicate if cap rock is silicified.	This could be another good method for continuously monitoring reservoir activity.

CHART III. GEOLOGIC CLASSIFICATIONS AND METHODS FLOW CHART

GEOLOGIC SITUATIONS		EVALUATION METHODS							
I. Geothermal fields primarily associated with recent volcanics and structures caused by:	A. Volcanic processes (calderas and volcanoes)	1) Review of existing information including: maps, publications, reports, data sheets and graphs, air photographs, and laboratory reports.	2) Geologic field work and mapping, including general survey for surface manifestations and basic study of surface deposits and alterations.	3) Geochemical analyses of springs, rivers and lakes including: a. water analysis for temp. and system type, b. deposit analysis for temp., c. isotope fraction analysis for water history, and d. gas analysis for supporting data.	4) Telluric methods for structure and temperature indications at depth.	5) a. Surface or shallow direct heat flow measurements. b. Shallow electromagnetic induction soundings for supporting heat flow data.	6) a. Intermediate depth heat flow measurements for direct thermal gradient and reservoir temp. indications. b. General resistivity survey for rock permeability, temp. and structure.	7) Supporting structural methods: a. magnetics b. gravitation c. seismic	8) Miscellaneous supporting data: a. self-potential b. remote sensing c. seismic noise 9) Drill test hole
	1. light groundcover and/or flat terrain:								
	2. heavy groundcover and/or rough terrain:								
	3. submerged lands:								
	B. Tectonic processes (faults and grabens)	1) Review of existing information including: maps, publications, reports, data sheets and graphs, air photographs, and laboratory reports.	2) Geologic field work and mapping, including general survey for surface manifestations and basic study of surface deposits and alterations.	3) Geochemical analyses of springs, rivers and lakes including: a. water analysis for temp. and system type, b. deposit analysis for temp., c. isotope fraction analysis for water history, and d. gas analysis for supporting data.	4) Telluric methods for structure and temperature indications at depth. Self-potential for simplicity in rugged terrain.	5) a. Shallow electromagnetic induction soundings for heat flow data. b. Shallow direct heat flow measurements, if possible, for supporting heat flow data.	6) General reconnaissance airborne methods including: a. remote sensing b. gravitation c. magnetics	7) a. Intermediate heat flow measurement for direct reservoir temp. b. Resistivity survey for rock permeability, temp. and structure	8) Miscellaneous supporting data: a. seismic b. seismic noise 9) Drill test hole
	1. light groundcover and/or flat terrain:								
	2. heavy groundcover and/or rough terrain:								
	3. submerged lands:								
	B. Tectonic processes (faults and grabens)	1) Review of existing information including: maps, publications, reports, data sheets and graphs, air photographs, and laboratory reports.	2) Geologic field work and mapping, including general survey for surface manifestations and basic study of surface deposits and alterations.	3) Geochemical analyses of springs, rivers and lakes including: a. water analysis for temp. and system type, b. deposit analysis for temp., c. isotope fraction analysis for water history, and d. gas analysis for supporting data.	4) Telluric methods for structure and temperature indications at depth. Self-potential for water circulation along faults.	5) a. Shallow electromagnetic induction soundings for heat flow data. b. Shallow direct heat flow measurements, if possible, for supporting heat flow data.	6) a. Intermediate depth heat flow measurements for direct thermal gradient and reservoir temp. indications. b. General resistivity survey, if possible, for rock permeability, temp. and structure.	7) Telluric methods along shoreline, if possible, for depth data.	8) Drill test hole
	1. light groundcover and/or flat terrain:								
	2. heavy groundcover and/or rough terrain:								
	3. submerged lands:								
II. Geothermal fields not primarily associated with recent volcanics:	A. Tectonic processes	1) Review of existing information including: maps, publications, reports, data sheets and graphs, air photographs, and laboratory reports.	2) Geologic field work and mapping, including general survey for surface manifestations and basic study of surface deposits and alterations.	3) Geochemical analyses of springs, rivers and lakes including: a. water analysis for temp. and system type, b. deposit analysis for temp., c. isotope fraction analysis for water history, and d. gas analysis for supporting data.	4) Telluric methods for structure and temperature indications at depth. Self-potential for water circulation along faults.	5) a. Shallow electromagnetic induction soundings for heat flow data. b. Shallow direct heat flow measurements, if possible, for supporting heat flow data.	6) General reconnaissance airborne methods including: a. gravitation (structural) b. magnetics (structural) c. remote sensing	7) a. Intermediate heat flow measurement for direct reservoir temp. b. Resistivity survey for rock permeability, temp. and structure.	8) Miscellaneous supporting data: a. seismic b. seismic noise 9) Drill test hole
	1. light groundcover and/or flat terrain:								
	2. heavy groundcover and/or rough terrain:								
	3. submerged lands:								
	B. Basins where faulting does not play a major role:	1) Review of existing information including: maps, publications, reports, data sheets and graphs, air photographs, and laboratory reports.	2) Geologic field work and mapping, including general survey for surface manifestations and basic study of surface deposits and alterations.	3) Geochemical analyses of springs, rivers and lakes including: a. water analysis for temp. and system type, b. deposit analysis for temp., c. isotope fraction analysis for water history, and d. gas analysis for supporting data.	4) a. Surface or shallow heat flow measurements. b. Shallow electromagnetic induction soundings for supporting heat flow data. c. Telluric methods for structure and temp. at depth.	5) a. Intermediate depth heat flow measurements for direct thermal gradient and reservoir temperature indications. b. General resistivity survey for rock permeability, temperature, and structure.	6) Supporting structural methods including: a. gravitation b. seismic c. magnetics (may be difficult to interpret)	7) Miscellaneous supporting data: a. self-potential b. remote sensing c. seismic noise	8) Drill test hole.
	1. light groundcover and/or flat terrain:								
	2. heavy groundcover and/or rough terrain:								
	3. submerged lands:								
	B. Basins where faulting does not play a major role:	1) Review of existing information including: maps, publications, reports, data sheets and graphs, air photographs, and laboratory reports.	2) Geologic field work and mapping, including general survey for surface manifestations and basic study of surface deposits and alterations.	3) Geochemical analyses of springs, rivers and lakes including: a. water analysis for temp. and system type, b. deposit analysis for temp., c. isotope fraction analysis for water history, and d. gas analysis for supporting data.	4) a. Shallow electromagnetic induction soundings for heat flow data. b. Telluric methods for structure and temp. at depth. c. If possible, shallow direct heat flow measurements for supporting data.	5) a. Intermediate depth heat flow measurements for direct thermal gradient and reservoir temperature indications. b. General resistivity survey for rock permeability, temperature, and structure. c. Self-potential.	6) General reconnaissance airborne methods including: a. remote sensing b. gravitation c. magnetics (may be difficult to interpret).	7) Miscellaneous supporting data: a. seismic b. seismic noise	8) Drill test hole.
	1. light groundcover and/or flat terrain:								
	2. heavy groundcover and/or rough terrain:								
	3. submerged lands:								
	B. Basins where faulting does not play a major role:	1) Review of existing information including: maps, publications, reports, data sheets and graphs, air photographs, and laboratory reports.	2) Geologic field work and mapping, including general survey for surface manifestations and basic study of surface deposits and alterations.	3) Geochemical analyses of springs, rivers and lakes including: a. water analysis for temp. and system type, b. deposit analysis for temp., c. isotope fraction analysis for water history, and d. gas analysis for supporting data.	4) a. Surface or shallow heat flow measurements directly into submerged land. b. Supporting electromagnetic induction sounding if possible. c. Self-potential survey (simple on water).	5) a. Intermediate depth heat flow measurements for direct thermal gradient and reservoir temperature indications. b. General resistivity survey for rock permeability, temperature, and structure. c. Self-potential.	6) General reconnaissance techniques either airborne or on ship: a. gravitation b. magnetics c. remote sensing d. seismic For structural, alteration and temp. indications.	7) Telluric methods along shoreline, if possible, for depth data.	8) Drill test hole.
	1. light groundcover and/or flat terrain:								
	2. heavy groundcover and/or rough terrain:								
	3. submerged lands:

Table #1

Identified Hot-Water Convection Systems with Indicated Subsurface
Temperatures Above 150 degrees Centigrade - Renner and Other (1975)

Location			Temperatures °C				Reservoir Assumptions			
Name	Latitude N	Longitude W	Surface 1/	Geochemical 2/ SiO ₂	Geochemical 2/ Na-K-Ca	Sub- surface 3/	Sub- surface area km ² 4/	Thick- ness km 5/	Vol- ume km ³ 6/	Heat con- tent 10 ¹⁸ cal 7/
CALIFORNIA										
Surprise Valley	41 40	120 12	97	174	159	175	125	2	250	24
Morgan Springs	40 23	121 31	95	190	229	210	5	2	10	1.2
Sulphur Bank mine	39 01	122 39	80	181	157	185	2.5	1.5	3.75	.4
Calistoga	38 34.9	122 34.4		157	155	160	4.5	2	9	.8
Skagg's H.S.	38 41.6	123 01.5	57	150	153	155	2	1.5	3	.3
Long Valley	37 40	118 52	94	219	238	220	225	2	450	55
Red's Meadow	37 37	119 04.5	49	161	130	165	1.5	1.5	2.25	.2
Coso H.S.	36 03	117 47	95	161	238	220	168	2	336	41
Sespe H.S.	34 35.7	118 59.9	90	133	155	155	1.5	1.5	2.25	.2
Salton Sea	33 12	115 36	101			340	54	2	108	21
Brawley	33 01	115 31				200	18	1.5	27	3
Heber	32 43	115 31.7				190	50	2	100	11
East Mesa	32 47	115 15				180	28	2	56	5.5
Border	32 44	115 07.6				160	3	.6	1.8	0.2

Table #2

Chemical Composition of Rivers and Lakes - Livingstone (1963, pp.16-17)

CHEMICAL COMPOSITION OF RIVERS AND LAKES

Analyses, in parts per million, of water from the Basin-Range province and adjacent closed basins

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
HCO ₃ ⁻	232	18,165	16,668	26,430	69	1187	1639	55	48	571	1,300	1870	1,200	2,040	53	6,296
SO ₄ ⁻²	4,139	<10	21.8	7,530	8.5	4,960	237	2.0	1.0	135	264	1.6	307	576	1.2	103,680
F ⁻	1.6			23	.2	4.9	4.8	.1	.1		.8	7.0	10	6.0		
Cl ⁻	9,033	905	5,945	15,100	1.0	21,400	109	3.5	2.2	1,725	1,960	22	1,160	2,330	1.2	1,668
NO ₃ ⁻	1.3			2.4	.2		.50	.1	.0		1.6	2.2	.4	3.5	.3	
PO ₄ ⁻³				38												
Ca ⁺²	505	8	Nil	11	13	1,230	2.0	9.2	8.4	20	10	4.5	6.9	17	7.6	640
Mg ⁺²	581	24	30.7	32	2.5	148	.2	3.2	2.7	15	113	49	.9	8.9	2.9	22,838
Sr ⁺²		5.3		96			.23									
Li ⁺	1.9	1.2		8.5			16									
Na ⁺	6,249	3,390	6,199	21,400	9.2	14,100	423	6.1	4.8	1,821	1,630	220	1,370	3,180	6.5	7,337
K ⁺	112	731	332	1,120	2.3	904	17.1	1.6	1.4	70	134	59	11	7.5	2.1	801
B.....	5.0	360	221	157	.10	60	.84	.00	.00			.03	19	38		
Fe.....				.21			.00	.00	.03		.00	.03	1.3	.08		
SiO ₂	20.8	20		.0	41	49	70.0	9.6	16	28	1.4	10	63	28	33	
Specific gravity.....	1.012	1.006	1.009	1.0470												
Total dissolved solids.....	20,900	13,600	>19,400	71,900	147	42,700	1,520	90.4	84.1	3,890	5,510	1,250	4,150	9,240	108	>143,000

1 Includes CO₂.

- A. Salton Sea near Nullett Island, Imperial County, Calif. Collected Feb. 3, 1954. Unpublished U.S. Geol. Survey analysis by Henry Kramer.
 B. Little Borax Lake, Lake County, Calif. Collected Oct. 6, 1956. Unpublished U.S. Geol. Survey analysis by C. E. Roberson.
 C. Borax Lake, Lake County, Calif. Collected Mar. 24, 1954. Unpublished U.S. Geol. Survey analysis by Henry Kramer.
 D. Mono Lake near Lee Vining, Mono County, Calif. Collected Sept. 11, 1956. Unpublished U.S. Geol. Survey analysis. Cu and Zn looked for but not found.
 E. Rush Creek near Mono Lake, Calif. Collected Oct. 21, 1953. U.S. Geol. Survey (1953a).
 F. Pons at Bad Water, Death Valley, Calif. Collected April 17, 1954. U.S. Geol. Survey (1955a).
 G. Amargosa River near Beatty, Nev. Unpublished U.S. Geol. Survey analysis.
 H. South end of Lake Tahoe at Bijou, Nev. Collected Sept. 21, 1953. U.S. Geol. Survey (1953a).
 I. Truckee River at Farad, Calif. Collected Sept. 22, 1953. U.S. Geol. Survey (1953a).
 J. Winnemucca Lake, Nev. Clarke (1924b, p. 160).
 K. Pyramid Lake at Sutcliffe, Nev. Collected Sept. 19, 1953. Unpublished U.S. Geol. Survey analysis.
 L. Eagle Lake near Susanville, Calif. Collected May 4, 1954. Unpublished U.S. Geol. Survey analysis.
 M. Lower Alkali Lake near Eagleville, Calif. Collected May 5, 1954. U.S. Geol. Survey (1955a).
 N. Middle Alkali Lake near Cedarville, Calif. Collected May 5, 1954. U.S. Geol. Survey (1955a).
 O. Abert Lake near Valley Falls, Oreg. Collected Aug. 21, 1956. Unpublished U.S. Geol. Survey analysis.
 P. Hot Lake, Wash. Collected Aug. 23, 1955. Analysis by Bur. Reclamation, Eng. Laboratories Branch, Denver, Colo., in Anderson (1958, p. 267).

Analyses, in parts per million, of water from the Colorado River system and the Sacramento River

	A	B	C	D	E	F	G	H	I
HCO ₃ ⁻	42	107	256	179	235	163	183	79	62
SO ₄ ⁻²	5.2	101	794	230	231	256	289	11	5.2
F ⁻	.3	.2	.2	.3	.3	.3	.2	.4	.0
Cl ⁻	1.1	35	24	49	70	75	113	7.1	4.0
NO ₃ ⁻	0.8	1.8	2.0	2.2	1.9	1.4	1.0	.6	.9
Ca ⁺²	9.6	55	145	75	91	84	94	12.9	14
Mg ⁺²	1.9	11	81	28	28	27	30	7.0	2.7
Na ⁺	3.5	26	166	70	80	88	124	10.5	7.7
K ⁺	2.7	2.8	6.1	4.0	5.8	2.9	4.4	1.3	.9
B.....	.00	.00					.052	.10	.010
Fe.....	.14	.00	.06	.03	.09	.05	.01	.08	.112
Al.....							.012	.06	0.60
SiO ₂	8.3	7.4	9.9	12	14	13	14	19	20
Total dissolved solids.....	76.8	351	1,400	650	757	711	833	149	117

- A. Colorado River at Hot Sulphur Springs, Colo. Oct. 1948 to Sept. 1949. U.S. Geol. Survey (1953b).
 B. Eagle River below Gypsum, Colo. Oct. 1948 to Sept. 1949. U.S. Geol. Survey (1953b).
 C. San Rafael River near Green River, Utah. Oct. 1948 to Sept. 1949. U.S. Geol. Survey (1953b).
 D. Colorado River at Lees Ferry, Ariz. Oct. 1949 to Sept. 1950. U.S. Geol. Survey (1954d [1953]).
 E. Colorado River near Grand Canyon, Ariz. Oct. 1949 to Sept. 1950. U.S. Geol. Survey (1954d [1953]).
 F. Yuma main canal below Colorado River siphon at Yuma, Ariz. Oct. 1949 to Sept. 1950. U.S. Geol. Survey (1954d [1953]).
 G. Colorado River at bridge on U.S. Highway 80 at Yuma, Ariz. Sept. 16, 1955. Durum, Heidel, and Tison (1960). Analysis includes Ag, 0.0010 ppm; Ba, 0.152 ppm; Co, 0.000 ppm; Cr, 0.024 ppm; Cu, 0.0083 ppm; Li, 0.035 ppm; Mn, 0.021 ppm; Mo, 0.0069 ppm; Ni, 0.030 ppm; P, 0.000 ppm; Pb, <0.0080/ppm; Rb, <0.0080 ppm; Sr, 0.802 ppm; Tl, <0.0080 ppm; and Zr, 0.000 ppm;
 H. Sacramento River at Rio Vista, Calif., 1950. California Dept. of Water Resources (1957, p. A-282).
 I. Sacramento River at tower bridge on Capital Street, Sacramento, Calif. Nov. 25, 1958. Durum, Heidel, and Tison (1960). Analysis includes Ag, <0.00006 ppm; Ba, 0.631 ppm; Co, 0.000 ppm; Cr, 0.0044 ppm; Cu, 0.0029 ppm; Li, 0.0021 ppm; Mn, 0.0065 ppm; Mo, <0.00043 ppm; Ni, 0.0071 ppm; P, 0.000 ppm; Pb, 0.0045 ppm; Rb, 0.0010 ppm; Sr, 0.046 ppm; Tl, <0.00086 ppm; and V, <0.086 ppm.

TABLE #3

Summary of Geochemical Methods Techniques for Analysis

A. <u>Analysis of Hydrothermal Water:</u> (for chemical geothermometers)	<u>Techniques for Analysis:</u>
1) SiO_2 2) Na/K 3) Na/Ca 4) Mg/Ca 5) Cl 6) Cl/F 7) Cl/B 8) Ca and HCO_3 9) S	1) gravimetric 2) volumetric 3) colorimetric 4) X ray emission 5) flame emission 6) polarography 7) neutron activation 8) emission spectroscopy
B. <u>Analysis of Gas:</u>	
1) H_2S 2) CO_2 3) NH_3 4) various ratios	1) volumetric 2) emission spectroscopy 3) absorption spectroscopy 4) mass spectroscopy 5) gas chromatography
C. <u>Analysis of Deposits:</u>	
1) Hg 2) SiO_2 3) CaCO_3 4) radioactivity	1) gravimetric 2) volumetric 3) field methods 4) instrumental methods
D. <u>Analysis of Isotope Fractions:</u>	
	1) mass spectroscopy 2) neutron activation
E. <u>Miscellaneous Analysis:</u>	
1) heavy mineral analysis 2) pH analysis 3) rate of discharge	1) same techniques as water analysis

TABLE #4

Summary of Geophysical Methods and Techniques

- A. Seismic - active methods including reflection and refraction
- B. Seismic - passive methods including seismic noise and micro-seismology
- C. Gravity
- D. Magnetism
- E. Heat Flow - shallow and surface measurements (30 meter maximum)
- F. Heat Flow - intermediate depths (30-200 meter maximum)
- G. Direct Current Resistivity - including induced polarization
- H. Inductive Methods - excluding tellurics
- I. Self-Potential
- J. Telluric Methods - including tellurics, magnetotellurics, and audiomagnetotellurics
- K. Remote Sensing Techniques

IV. GEOLOGIC CLASSIFICATION SYSTEM

The literature of geothermal systems is supplied with a number of models and geologic classifications of these systems. (Duprat and Omnes, in press; Tonani, 1970; and McNitt, 1970 are a few.) The varied geologic situation with examples is given by Duprat and Omnes (in press); "The geological nature of steam or hot water reservoirs is variable:

fractured dolomitic limestones and quartzites(Larderello) 'Italy'
fractured and porous limestones (Kizildere) 'Turkey'
fractured graywackes (The Geysers) 'California'
fractured sandy shales (Cerro Prieto) 'Mexico'
tuff breccia (Otake, Broadlands) 'Japan, New Zealand'
breccia (Broadlands)
fissured and silicified rhyolite (Broadlands)
fractured marbles and calc-schists (Kizildere)

These reservoir formations are generally fractured competent rocks. Their matrix is electrically resistive, but they may behave as conductive markers when pores and joints are filled with a conductive fluid which may be a cold brine or hot water.

In most cases an impervious or almost impervious cap rock overlies the geothermal reservoir. A distinction may be made between two types of cap rocks: (1) a conductive clayey horizon formed independently from the geothermal activity; and (2) a resistive or conductive formation where self-sealing took place.

.....where the cap rock belongs to the first type as in the following geothermal fields:

Larderello: "scagliose" clays (Upper Cretaceous to Eocene)
Viterbo: Pliocene clays and flysch underlying volcanics
Kizildere: Miocene clays and shales
Cerro Prieto: clayey delta sediments
Salton Sea: clay and silt beds of Pleistocene and Holocene age

.....where the cap rock belongs to the second type as in the following geothermal fields:

1. The Geysers. From surface to bottom the wells penetrate the

fractured graywackes and basalts of the Franciscan formation (Jurassic and Cretaceous). Cores show that in the upper sections of the holes fissures are filled with silica; moreover, the graywackes are argillized (Facca, 1965).

2. Broadlands. The Broadlands rhyolite acts as a cap for underlying steam reservoirs. The low porosity is due to extensive silication (Grindley, 1970).
3. The Dunes geothermal anomaly (Imperial Valley). Silica precipitation in sandstones trapped hot brine at a depth of 300 m (Bird and Elders, 1974).
4. Matsukawa. The upper part of the welded tuff formations is argillized
5. Otake. Pyroxene andesite lavas altered into montmorillonite play the role of cap rock overlying a zeolitized tuff breccia ...
6. The Ahuachapan area (El Salvador). Granitic rocks are kaolinized (Facca, 1967).

Facca (1965) defines a self-sealing geothermal field as 'a geothermal field in which hydrothermal activity has generated a cap rock by transforming originally permeable rocks into low permeability rocks in such a manner and with such geometry, to constitute an efficient trap for convection current. The basic process of the self-sealing are the rock alteration, in the first place kaolinization, and the filling of the voids by deposition of different minerals, most commonly silica and calcite.' (Facca, 1967)."

The geologic classification system in this paper must be broad to include these various situations and specific to show where one may expect particular geological, geochemical, or geophysical detection problems. This paper contains two classification systems.

The first is a detailed and specific classification shown on Chart I., Geologic Classification and Geothermal Detection Methods. A number of geothermal areas are included in this chart to illustrate how a given area may be classified. Also, detection methods which might be expected to supply significant data for the classifications are shown. More detailed information concerning the specific examples are given in the next section.

A more general classification is included in Chart III., Geologic Classifications and Methods Flow Chart. Detection methods, in preferential order, are shown for each geologic category within the classifications.

The following are specific examples of geothermal systems.

1. Salton Sea Area, California: 35 square kilometers - near 5 small volcanos - hot spring activity - highly faulted - shale, siltstone, and clay - 700-1000 meters thick - grades into arkosic sand 700 meters thick - 5 small rhyolitic plugs - open fractures - sedimentary section with 15 degree dip - sills and dikes - sediments in contact with sills, etc. are altered - volcanics intersected by wells - sandstone is reservoir rock with clay as insulator - gravity and magnetic anomalies (Helgeson, 1968).

Classification - Chart I.

II. Geothermal fields not primarily associated with volcanics

A. Fault block structure

1) ground water in sedimentary rocks

b. reservoir depth - greater than 500 meters
(interbedded sandstone and shale)

2. The Geysers - Clear Lake, California: Only example of a large vapor-dominated system extensively drilled in the United States - hot springs, etc. - no large caldera collapse structures evident - Franciscan graywackes - some basalts, serpentines, etc. - recent volcanic activity (Quaternary) - fractured cap rock and reservoir are Franciscan graywackes - well depth 300-1400 meters - highly fractured and faulted - heat source is suspected to be rhyo-dacite volcanic plug (Pleistocene) - (Koenig, 1970; McMillan, 1970; McNitt, 1963; and Urban and others, in press)

Classification - Chart I.

I. Geothermal fields primarily associated with volcanics and structures caused by:

B. Tectonic processes

2) faults and fault intersections

a. and b. greater than 250 meters

3. Casa Diablo and Long Valley, California: Visible springs, localized along steeply dipping faults - collapse caldera structure - deepest well approximately 300 meters - recent volcanics - basalt flows over lake deposits - dense body at 1000 meters may be a volcanic or intrusive heat source - hydrothermal alteration by fumeroles and hot springs (Bailey and others, 1976; Muffler and Williams, 1976; and McNitt, 1963).

Classification - Chart I.

I. Geothermal fields primarily associated with volcanics and structures caused by:

A. Volcanic processes

1) caldera and caldera rims

a. and b. reservoir depth greater than 250 meters

4. Mount Lassen, California: Historic volcanic activity - hot springs issue from andesite and breccias - many of the principal hot springs are found within the frontal cladera of Brokeoff cone - rocks around springs are altered (MacDonald, 1966, p.79) - possible vapor-dominated system - (another possible vapor-dominated system is Yellowstone National Park)(Renner and others, 1975)

Classification - Chart I.

I. Geothermal fields primarily associated with volcanics and structures caused by:

A. Volcanic processes

1) calderas and caldera rims

a. reservoir depth less than 500 meters

5. Steamboat Springs Area, Nevada: Springs at surface - silicious and carbonate deposits - 3 fault systems - long history of volcanism through Tertiary and Quaternary - large 50 square kilometer magma chamber - all springs emerge from topographic lows - some alluvium, widespread sinter deposits, and basaltic andesite flows over intruded granodiorite and Kate Peak flows of various volcanics (White and others, 1964).

Classification - Chart I.

I. Geothermal fields primarily associated with volcanics and structures caused by:

A. Volcanic processes

- 1) calderas and caldera rims
- a. and b. reservoir depth (?)

6. Marysville, Montana: "Blind area" with no surface indications - Tertiary volcanics and Paleozoic sediments over Precambrian shales and limestones - cut by various intrusives, largest is the Marysville stock (Cretaceous) - several dikes and sills - several high angle faults - stock surrounded by broad belt of contact metamorphism of sedimentary rocks - no springs or recent volcanics - initially surveyed by heat flow methods - a test well has been drilled, and linear temperature gradient was measured reaching a maximum temperature of 95 degrees C at 500 meters - at lower depths no further temperature increase was recorded - (Blackwell and Baag, 1973 and Blackwell and Morgan, 1975)

Classification - Chart I.

II. Geothermal fields not primarily associated with volcanics:

B. Basins where faulting does not play a major role:

(Based on recent heat flow data, this prospect may not contain a geothermal reservoir.)

V. GEOLOGIC METHODS FOR DETECTION OF GEOTHERMAL SYSTEMS

The geologic detection and survey methods are broken into five broad categories:

A. Studying surface manifestations including:

1) fum ² erole	4) recent volcanism
2) hot springs	5) calderas and caldera rims
3) geysers	6) lake settings

The most obvious surface indicators of geothermal reservoirs are leakage manifestations from a boiling water table. The identification of surface or leakage manifestations are not proof of an economic geothermal reservoir in the area. Additional geochemical and geophysical data are needed.

The problems of detecting these manifestations are discussed by Meidav and Tonani (in press): "In reservoirs which are sufficiently close to the boiling point, steam will flash off as a consequence of a comparatively small decrease in reservoir pressure. A steady flow of steam can be triggered either naturally, along fractures or joints, or can be artificially induced by drilling. Such a flow will be naturally sustained as long as the density of the water-steam mixture in the joint or borehole is lower than that of the formation water. Surrounding conditions will affect the characteristics of the discharge in both natural and artificial thermal fluid flows. For example, infiltration of cooler water into the hydrothermal system may change it from a steady-state steam flow to a geyser-like action or to complete quenching. The outlet of the steam discharge can also be variable: it can vent itself to the atmosphere, it can be released at the bottom of a water pool, or it can be discharged into the saturated or unsaturated groundwater zone beneath the surface. A great variation in the nature of leakage, from the visually obvious to the barely discernible, can occur in different settings. It is the latter that is the object of exploration, since the former does not require much sophistication for its discovery. The real exploration problem is that of detecting minute traces of steam

leakage in large bodies of water, and the regional assessment of such leakage manifestations."

B. Field mapping of:

- 1) faults and fractures
- 2) calderas and collapse structures
- 3) domes
- 4) intrusives
- 5) extrusives

C. Studying hydrothermal deposits and alterations:

- 1) opalization and silica cementation
- 2) siliceous sinter
- 3) argillization - a. kaolinite b. montmorillonite c. illite
- 4) zeolitization

D. Analyzing in the laboratory including:

- 1) radioactive dating
- 2) rock and mineral composition

E. Reviewing existing information:

- 1) air photographs: lakes (submerged lands) may occur in calderas, fault areas, grabens, etc.
- 2) geologic maps and literature

references:

- 1) Bailey and others, 1976
- 2) Healy, 1970
- 3) Meidav and Tonani, in press
- 4) Muffler and Williams, 1976

VI. GEOCHEMICAL METHODS FOR DETECTION OF GEOTHERMAL SYSTEMS

(For summary of methods and techniques for analysis see Table #3)

A. Analysis of Hydrothermal Water: This area of geochemical surveying consists of collecting water samples from hot or cold springs, rivers or lakes and analyzing these samples either at the sample site or in the laboratory. The geochemical analysis of these samples can provide information about subsurface geothermal conditions. Analysis techniques are described in a later section. Depending on the type of analysis, information can be developed concerning reservoir location, reservoir temperature, type of system (hot water or vapor), reservoir size, reservoir insulation, rock permeability, aquifer homogeneity, and miscellaneous information including corrosion possibilities.

A number of authors including Fournier and Truesdell (1973, p.1255) state that of all the water analysis methods available, only two are both quantitative and qualitative: 1) the variation of SiO_2 as a function of temperature, and 2) the temperature dependence of base exchange or partitioning of alkalis between solutions and solid phases (Na/K, Na/Ca, and Mg/Ca). Tables #1 and #2 show the chemical analysis for various hydrothermal systems.

1. brief description:

- a. SiO_2 - This may be the best geochemical indicator of reservoir temperature (White, 1970; Tonani, 1970; Mariner and Willey, 1976; and Ellis, 1970). Assumes quartz is at equilibrium at high temperature with no dilution or precipitation after cooling. The form of silica (quartz, cristobalite, amorphous silica) will affect solubility. Therefore assumptions about mineral assemblage can be critical (Meidav and Tonani, in press).
- b. Na/K - This is one of the most reliable geothermometers.

$$\text{equilibrium constant} = K_e = \frac{(\text{K-feldspar})(\text{Na}^+)}{(\text{Na-feldspar})(\text{K}^+)}$$

$$\text{and } \frac{d \log K_e}{d \log(1/T)} = \frac{\Delta H}{4.5758}$$

Ca content should be taken into consideration, and there may be interpretation problems (Fournier and Truesdell, 1973).

Also, three distinct geochemical environments or processes can have an effect on the Na/K vs. temperature ratio: hydrothermal, magmatic, and surface water (Meidav and Tonani, in press).

- c. Na/Ca - High ratio may indicate high temperature reservoir (White, 1970, p.70).
- d. Mg/Ca - Low ratio may indicate high reservoir temperature (White, 1970, p.70) and low Mg content alone can indicate high temperature - at high temperatures Mg favors the solid phase.
- e. Cl - High chloride content indicates hot water systems. (example - 200 mg/l in Long Valley, California; Mariner and Willey, 1976, p.797). Cl analysis permits detection of shallow mixing (White, 1970, p.71)
- f. Cl/F - High ratio may indicate high reservoir temperatures (White, 1970) as CaF_2 decreases in solubility with increasing temperature.
- g. Cl/B - Used to distinguish aquifers. Waters from the same aquifer have chemical compositions with almost constant Cl/B ratios regardless of bicarbonate concentrations (example - ratios are 5.7 ± 0.1 for most of the hot springs in the Long Valley area; Mariner and Willey, 1976, p.796).
- h. Ca and HCO_3 - Low concentrations of Ca and HCO_3 in near neutral pH waters may indicate high reservoir temperatures (Ellis, 1970).
- i. $\text{Cl}/\text{HCO}_3 + \text{CO}_3$ - The ratio decreases as spring temperature decreases. Can be used to determine if water is coming from different aquifers (Fournier and Truesdell, 1970, p.535). The highest ratios in related waters indicate highest subsurface temperatures (White, 1970, p.64).
- j. S - Analysis of S content for corrosion possibilities (Ellis, 1970, p.526). $4\text{H}_2\text{O} + 4\text{S} = 3\text{H}_2\text{S} + \text{H}_2\text{SO}_4$

2. advantages:

- a. These techniques provide a variety of qualitative and quantitative information about reservoirs, not just related to reservoir

location.

- b. For most techniques cost is an advantage.
- c. Some analysis work can be done in the field.
- d. Water sampling can be done in submerged land environments.
Because of water mixing and diffusion, there could be data interpretation problems..

3. disadvantages:

- a. Various water mixing and rock-water assumptions must be made.
- b. Many of the methods cannot be done in the field.
- c. There may be some collection and contamination problems.
- d. Original temperature of a fluid emanating at the surface may not be economically significant if depth related information is lacking (Meidav and Tonani, in press). Also there may be data interpretation problems, and no single method should be used by itself as a geothermal indicator.

4. geologic considerations:

- a. These basic assumptions must be made for geothermometers:
 - 1) There is negligible mixing of thermal fluids with other waters. (Near-surface cold water mixing can be considered using Fournier-Truesdell mixing models, based on SiO_2 and temperature of cold and warm water sources - Fournier and Truesdell, 1974)
 - 2) There are negligible water-rock reactions at lower temperatures.
 - 3) There are temperature dependent reactions with adequate supply of constituents in the local reservoir rocks.
 - 4) There is a rapid flow of water from reservoir to spring (White, 1970, p.64).
- b. Surface springs must be available for direct sampling. Streams and lakes can also be sampled.
- c. Samples should be taken from the springs with the highest discharge, temperature and chloride content (White, 1970, p.64).
- d. In order to postulate meaningful temperature models, it is usually necessary to make a regional hydrogeochemical survey,

using a number of geochemical methods. It should be established if data from these methods are in balance (Meidav and Tonani, in press).

5. references:

- a. Arnorsson, 1970 (silica content)
- b. Ellis, 1970 (silica content, Na/K ratio, pH, and minerals)
- c. Fournier and Truesdell, 1970 (general)
- d. Fournier and Truesdell, 1973 (Na - K - Ca thermometer)
- e. Fournier and Truesdell, 1974 (water mixing models)
- f. Livingstone, 1963 (general lake and river analysis)
- g. Mariner and Willey, 1976 (general and field techniques)
- h. Meidav and Tonani, in press (general "pitfalls")
- i. Tonani, 1970 (silica content, Na/K ratio, HCO_3 , and miscellaneous)
- j. White, 1970 (general)

B. Analysis of Gas: As stated by Finlayson (1970, p.1344), "A knowledge of the composition of the gas phase associated with various surface emanations of volcanic and geothermal systems forms an essential part of the study of these systems". As with hydrothermal water analysis, this method consists of taking samples at the site and then performing an analysis, usually in the laboratory. The collection of gas samples presents a problem as air must be excluded from the sample, and the composition of the gas mixture must be preserved. Information obtained from the analysis will usually be supporting data for the other geochemical detection methods. According to Mazor (1975) the presence or absence of noble gases can be an indicator of vapor or liquid dominated systems. Techniques for the analysis work are described in the next section.

1. brief description:

- a. H_2S - This gas is common to hydrothermal systems because of reducing conditions below the surface (Tonanai, 1970, p.510).
- b. CO_2 - Content decreases in water with increasing temperature and will have an effect on pH (Tonanai, 1970, p.510).
- c. NH_3 - This gas is also common to hydrothermal systems because

of reducing conditions.

- d. various ratios: H_2 /other gases - High ratios qualitatively indicate high temperature (White, 1970).

2. advantages:

- a. One of the few temperature indicators for vapor systems.
- b. Certain types of gas leakage may be indicative of hydrothermal systems.
- c. The presence or absence of noble gases can be used to distinguish between liquid or vapor dominated systems.

3. disadvantages:

- a. There must be a gas source - cannot be used in a "blind area".
- b. There may be gas collection, sampling, and contamination problems (Finlayson, 1970), particularly in submerged land environments.

4. geologic considerations:

- a. There must be gas leakage for sampling.
- b. All types of gas leakage may not be indicative of a geothermal area (Finlayson, 1970).

5. references:

- a. Ellis, 1970 (general)
- b. Finlayson, 1970 (gas collection and analysis)
- c. Fournier and Truesdell, 1970 (volatile concentrations)
- d. Mazar, 1975 (noble gases)
- e. Tonani, 1970 (B, NH_3 , and CO_2 content)
- f. White, 1970 (general)

C. Analysis of Deposits: This method consists of analyzing surface deposits from ascending hydrothermal waters or vapors. It can be considered a geologic technique and usually includes an on-site analysis, primarily for deposit type. The deposits are surface manifestations of ascending hydrothermal waters or vapors and can indicate relative water temperatures of the system.

1. brief description:

- a. Hg - Can be precipitated from hot spring water and may form Hg halos (Tunell, 1964 and Tonani, 1970, p.512).
- b. SiO_2 - "Siliceous sinter and natural geysers both imply high subsurface temperature - 180 degrees C or greater." (White, 1970, p.71).
- c. CaCO_3 - Travertine deposits imply a low temperature system (usually below 100 degrees C).
- d. radioactivity - CaCO_3 deposits are often radioactive due to presence of radium: SiO_2 deposits are generally non-radioactive (Wollenberg, 1975).

2. advantages:

- a. Deposits can be direct evidence of a high or low temperature system.
- b. Deposits can show circulation patterns.
- c. This is a simple and direct method which does not require laboratory analysis.

3. disadvantages:

- a. Deposits are not always evident.
- b. Travertine measurements are unreliable if water has contacted limestone after cooling.
- c. Hg deposits are not a temperature indicator.
- d. Deposits will usually provide limited geothermal information.

4. geologic considerations:

- a. Surface flow of waters must be slow for deposits to form.
- b. Deposits are surface manifestations which are not always evident.

5. references:

- a. Ellis, 1970 (general)
- b. Tonani, 1970 (Hg, Si, and general)
- c. Tunell, 1964 (Hg)
- d. White, 1970 (general) ,

e. Wollenberg, in press (radioactivity)

D. Analysis of Isotope Fractions: The following is a brief description of the physical-chemical isotope fractionations as presented by Mayne (1960, p.152). In regions of hydrothermal alteration, the equilibrium distribution of the oxygen isotopes between water and each mineral compound will be described by the respective equilibrium constant values. As the equilibrium constants are temperature dependent, the fractionation will depend on the temperature at which equilibrium was established. If the fractionation factors for a system are known, then the equilibrium temperature can be calculated. Differences in vapor pressure will have an effect on fractionations under equilibrium conditions. According to Mayne (1960, p.159), "When a material is taken out of a reservoir by a natural process it is characteristically labelled by its isotopic composition, in more than one manner in some cases, and thus forms a natural isotope tracer.". Caution must be used though, because a number of equilibrium and non-equilibrium processes can affect the fractionation. Isotope analysis of a geothermal system can be used as an indicator of the history of the geothermal water (source of the water and extent of fresh water mixing) and is also one of the few methods available to estimate the temperature of a vapor system.

1. advantages:

- a. Isotope fractions are a tracer of the history of geothermal water.
- b. This is one of the few methods used to determine the temperature of a vapor system.
- c. Data can be obtained concerning source of water for reservoir and age of recharging waters (White, 1970, p.59 and 74).

2. disadvantages:

- a. Precision analysis is required, and there can be contamination problems.
- b. Interpretation problems occur with complex systems.

3. geologic considerations:

- a. Water sources such as springs, lakes, or rivers must be available.

4. references:

- a. Ellis, 1970
- b. Mariner and Willey, 1976, p.796
- c. Mayne, 1960
- d. White, 1970

E. Miscellaneous Analysis: The three methods included in this category are: 1) rate of spring discharge, 2) heavy metal analysis, and 3) pH measurements.

1. brief description:

- a. Rate of spring discharge: Most authors such as White (1970, p.64) feel that the most reliable geochemical data are obtained from the spring with the highest rate of discharge. Also qualitative information concerning rate of mixing can be determined from the discharge rate.
- b. Heavy metal analysis: Certain hydrothermal waters contain high concentrations of heavy metals such as Cu, Fe, S, Ag, Sb, and As - as found in the Salton Sea waters (Ellis, 1970, p.527). Radioactive elements may also be an indicator (Bowman and others, in press).
- c. pH measurements: pH measurements of hydrothermal waters will aid in the interpretation of other geochemical data.

2. advantages:

- a. Rate of discharge will help determine which spring will provide the most reliable geochemical data.
- b. Under certain conditions, concentrations of heavy minerals may be an indicator of hydrothermal waters.

3. disadvantages:

- a. Determining rate of discharge may be difficult (White, 1970

p.64). Rough estimations without instruments may have to be made.

- b. Heavy mineral concentrations will be affected by pH variations.
- c. pH measurements may be misleading because of solution reactions with wall-rocks.
- d. In situ pH measurements may be difficult.

4. geologic considerations:

- a. These methods are only applicable for spring, river, and lake areas.

5. references:

- a. Bowman and others, in press (trace, minor, and major elements)
- b. Ellis, 1970
- c. White, 1970

VII. GEOCHEMICAL TECHNIQUES FOR ANALYSES

There are three basic categories of geochemical analytical techniques: 1) gravimetric, 2) volumetric, and 3) instrumental.

A. Gravimetric: The gravimetric method involves a weight determination for the measurements step. A separation, usually brought about by precipitation or electrolysis, accompanies this determination. Because of certain requirements necessary for a successful analysis, this method usually is performed in a laboratory, not at the sample site. According to Volborth (1969, p.44), "In some cases the classical gravimetric procedures are clearly superior in accuracy to all other methods, as in the case of silicon. Most standards available to the inorganic chemist are based mainly on gravimetric work.".

1. advantages:

- a. This method usually is more economical than instrumental methods.
- b. Gravimetric analysis is a familiar method with proven and reliable techniques.
- c. The method is versatile and can be used for a number of major elements.

2. disadvantages:

- a. The sensitivity is only in the parts per hundred range (Vincent, 1960).
- b. The techniques require skilled workers and should be done in a laboratory.
- c. Analysis cannot be performed for trace elements.

3. references:

- a. Day and Underwood, 1967, p.16
- b. Vincent, 1960, p.33
- c. Volborth, 1969, p.44

B. Volumetric: In volumetric analysis, the volume of a solution of

known concentration required to react with the desired constituent is measured. The method is also referred to as titrametric analysis. Four types of reactions may be used: 1) acid-base, 2) oxidation-reduction, 3) precipitation, and 4) complex formation.

1. advantages:

- a. This method is economical, and results are accurate and reproducible.
- b. Volumetric analysis is a classical method with proven and reliable techniques.
- c. Simplicity - no special instruments are needed - and speed offer advantages over the gravimetric method.

2. disadvantages:

- a. Sensitivity is in the parts per thousand range.
- b. Skilled workers are required, and analysis should be done in the laboratory.
- c. Analysis can be performed for major and some trace elements.

3. references:

- a. Day and Underwood, 1967, p.16
- b. Vincent, 1960, p.33
- c. Volborth, 1969, p.47

C. Colorimetric Methods including Spectrophotometry, Ultraviolet, and Visible Absorption: The following description is given by Volborth (1969, p.48), "In colorimetry we compare the intensity of a color in a sample solution of a known volume with the intensity of this color in solutions of known composition. The absorbance of the solutions is measured by a spectrophotometer, or estimated visually in a colorimeter by bracketing the unknown solution between solutions of known concentrations. In this method the intensity of colors of equal liquid columns is compared instead of known volumes being mixed to achieve a certain color change as in volumetry. In photometric titrations the optical density changes of a solution are measured during titration to detect the endpoint."

1. advantages:

- a. This method is more sensitive than gravimetric methods.
- b. Instrumentation is relatively inexpensive and has been developed for field use.
- c. Major and some trace elements can be analyzed.
- d. Speedy analyses can be made.

2. disadvantages:

- a. Not all major elements can be analyzed.
- b. Not as sensitive as other instrumental analytical techniques.
- c. Results may vary depending on techniques used, and it is possible to contaminate samples.

3. references:

- a. Martin, 1972, p.104 (chemical oceanography)
- b. Vincent, 1960, p.63 (geochemical analysis)
- c. Volborth, 1969, p.49 (geochemical analysis)
- d. Willard and others, 1974, chapter 3 and 4 (instrumental methods)

D. X ray Emission and X ray Fluorescence: According to Willard and others (1974, p.258), "X rays can be used in chemical analysis in several ways. One method uses the fact that the X rays emitted by an excited element have a wavelength characteristic of that element and an intensity proportional to the number of excited atoms. Thus emission methods can be used for both qualitative and quantitative work. The excitation can be carried out in several ways: by direct bombardment of the material with electrons (direct emission analysis and probe electron microanalysis) or by irradiation of the material with X rays of shorter wavelength (fluorescent analysis).".

The steps in the process are:

- 1) excitation of characteristic spectra from the sample
- 2) separation of the X ray lines for measurement
- 3) measuring the intensities of the lines
- 4) reducing the measurements to chemical composition

Excitation can be caused by:

- 1) high intensity X ray tube (X ray fluorescence)

- 2) electron beam (electron-probe for X ray microanalysis)
- 3) combination (ultra-soft X ray technique - versatile and sensitive but expensive)

1. advantages:

- a. The method is accurate, reproducible, and sensitive (parts per million).
- b. With special attachments this instrument can analyze most major and minor elements.
- c. The sample is not destroyed.
- d. The process is faster than the gravimetric or volumetric methods.
- e. A fast neutron generator can be added for neutron activation.

2. disadvantages:

- a. Special attachments make the instrumentation expensive.
- b. Without special attachments this method cannot be used for elements with an atomic number less than twelve (Volborth, 1969, p.235).
- c. Trained personnel may be required to perform analysis.

3. references:

- a. Adler, 1966
- b. Herbert and Bowman, in press
- c. Shalgosky, 1960, p.111
- d. Volborth, 1969, p.235
- e. Willard and others, 1974, p.258

E. Flame Emission (flame photometry) and Atomic Absorption Spectrometry: "Unlike the emission methods which are based on the excitation of atomic species by the heat of a flame and the measurement of emitted radiation as characteristic spectra, atomic absorption consists of the measurement of absorption caused by chemically unbound atoms in a flame.", according to Volborth (1969, p.194), "Whereas not more than 4% of the atoms of an element are raised to a high-energy level in conventional burners, the rest of the atoms, in an ideal case,

are merely stripped from their chemical bonds and remain at the ground state It is evident that atomic absorption should theoretically be more sensitive because the amount of atoms causing the effect may be orders of magnitude larger than in emission."

1. advantages:

- a. This method is accurate, precise, and sensitive to parts per billion.
- b. This is a relatively simple instrumental procedure.
- c. Compared to other instruments, the cost is reasonable.

2. disadvantages:

- a. The sample is destroyed
- b. The instruments are not designed for field use.

3. references:

- a. Angino and Billings, 1967
- b. Volborth, 1969, p.194
- c. Willard and others, 1974, chapter 12

F. Emission Spectroscopy: "Optical emission spectroscopy by electric arc or spark excitation is mainly a tool suitable for the determination of composition ranges from 0.3% to 1 p.p.m. based on the solid sample and using a photographic plate or direct metered readout.", Volborth, 1969, p.51. Development of direct reading photo-multiplier tubes have increased the range of this method.

1. advantages:

- a. Can be used for trace elements.
- b. Analyses can be done rapidly.
- c. The procedure is sensitive to parts per million.

2. disadvantages:

- a. Because of the upper limit of sensitivity, analysis is for trace elements only.
- b. This method is not as precise as X ray emission.

3. references:

- a. Ewing, 1960, chapter 5
- b. Volborth, 1969, p.51
- c. Willard and others, 1974, chapter 13

G. Polarography: Polarography is an electrochemical method involving the measurement of the limiting current during the reduction of a specific element at a specific potential, onto a mercury coated or dropping mercury electrode. There are a number of variations of this method including anodic stripping voltammetry whereby the sensitivity is increased by using a two step oxidation-reduction process.

1. advantages:

- a. Depending on the variation, polarography is sensitive in a range from parts per million to parts per billion.
- b. The procedure is selective of the elements to be analyzed.
- c. Analysis can be made rapidly.
- d. The cost is reasonable.

2. disadvantages:

- a. Most instrumentation is for laboratory use only, although some instruments have been developed for field use.
- b. Certain elements can cause intermetallic interference.

3. references:

- a. Ewing, 1960, p.195
- b. Willard and others, 1974, p.633

H. Neutron Activation Analysis: This process involves the production and measurement of a radioactive isotope by the capture of neutrons by the nuclei of the substance being analyzed. "The identification can be done by measurement of the half-life or the energy of the beta particles, or by analyzing the gamma-ray spectrum using scintillation methods or by a semiconductor detector and a multichannel analyzer.", Willard and others (1974, p.328)

1. advantages:

- a. The method is sensitive to parts per billion.
- b. The method is specific as the radioactivity induced is characteristic of the substance analyzed.
- c. There is minimal interference from the elements during the analysis.

2. disadvantages:

- a. There are a number of problems and precautions in creating radioactive isotopes.

3. references:

- a. Bowman and others, in press
- b. Volborth, 1969, p.278
- c. Willard and others, 1974, p.328

I. Mass Spectrometry: "The mass spectrometer produces charged particles consisting of the parent ion and ionic fragments of the original molecule, and sorts these ions according to their mass/charge ratio. The mass spectrum is a record of the numbers of different kinds of ions - the relative numbers of each are characteristic for every compound, including isomers.", Willard and others (1974, p.455).

1. advantages:

- a. This method can be used for gas analysis.
- b. Small sample sizes can be used - with special instrumentation samples of 10^{-8} ml can be analyzed.
- c. The method is sensitive to parts per million.

2. disadvantages:

- a. This is a laboratory instrument.

3. references:

- a. Finlayson, 1970, p.1352
- b. Willard and others, 1974, chapter 16

J. Gas Chromatography: Gas chromatography is a physical method of separation for measurement in which the components to be separated and measured are distributed between two phases, one phase constituting a large stationary surface area, the other a fluid that percolates along or through the stationary bed. The difference between solutes in their adsorption and interaction with the moving solvent becomes the basis of the separation when the solute molecules repeatedly distribute between the two phases throughout the length of the gas chromatography column (Day and Underwood, 1970, p.414). According to Finlayson (1970, p.1352), "The most suitable technique for the analysis of volcanic or hydrothermal gases is a gas chromatography. A number of advantages commend its use: it has a wide sensitivity range covering both major and minor components, a relatively small amount of sample is required (a few milliliters), it is relatively inexpensive and it is simple to operate.".

1. advantages:

- a. See preceding paragraph.

2. disadvantages:

- a. This instrument is not designed for field use.

3. references:

- a. Day and Underwood, 1967, p.416
- b. Finlayson, 1970, p.1352
- c. Willard and others, 1974, chapter 18

VIII. GEOPHYSICAL METHODS FOR DETECTION OF GEOTHERMAL SYSTEMS

(For summary of methods and techniques see Table #4)

A. Seismic - active methods including reflection and refraction:

Seismic refraction and reflection are methods whereby energy, from an artificial source, is transmitted through rock or water. In reflection seismology observations are made concerning the reflection of the transmitted energy from a discontinuity between two bodies of rocks with different elastic properties. According to Keen (1968, p.17), "Seismic reflection experiments are concerned with the reflection of energy at an interface, with the travel time between source and detector, and with amplitude and frequency of the reflected wave. Seismic refraction experiments differ from reflection experiments in the path of propagation: the energy we are concerned with is that which appears in terms of the travel time to be reflected at an interface between one medium and another"

Concerning seismic reflection: "This is a major geophysical method in oil exploration, but it has found relatively little use in geothermal work. This is mainly due to the different geological environments of these two energy resources. Most of the geothermal fields that have been explored so far are in volcanic areas where smooth sedimentary series are absent, or are highly disturbed by intrusions. The only case known where reflection method appears to have been used with some success is in the Matzukawa field in Japan (Hayakawa, 1970) On the other hand, seismic refraction appears to quite useful in volcanic areas, especially for structural studies in conjunction with gravity surveys, since the two physical properties, density and seismic velocity, are empirically related", (Palmason, in press). (Reflection vibroseis will be tried in New Mexico in May, 1976.)

1. advantages:

- a. Seismic methods can be used for the determination of structure, faults; fissures, horsts and grabens, etc. - lateral boundaries of reservoirs.

- b. Seismic techniques work well in submerged land environments.
- c. There is good depth penetration (5-6 km, Hill, 1976, p.752).
- d. This is an established geophysical technique, and much work has been done on data interpretation in submerged land environments.

2. disadvantages:

- a. This method can be expensive compared to other geophysical methods for structure. Energy sources will be needed in the field.
- b. The refraction seismic method may require a large area for surveying.
- c. Interpretation is applicable to structure only. (Possibly can detect hydrothermal alteration according to Hill, 1976, p.752).
- d. Data from these methods alone are not indicative of a geothermal area - should be used in conjunction with other structural methods such as gravity and magnetics.

3. geologic considerations:

- a. According to Duprat and Omnes (in press), "Seismic refraction is a more expensive but more accurate tool than gravity or high sensitivity aeromagnetometry for the determination of the depth to basement."
- b. Seismic techniques work well in submerged land environments - much work has been done on data interpretation and profiling of sub-bottom structure.

4. references:

- a. Banwell, 1970
- b. Barnes and others, 1972 (marine applications)
- c. Duprat and Omnes, in press
- d. Hayakawa, 1970
- e. Hill, 1976
- f. Hochstein, 1970
- g. Keen, 1968 (general -, geophysical methods in marine environments)

h. Palmason, in press

B. Seismic - passive methods including seismic noise and microseismology: Seismic noise analysis is a relatively new method, and there are still problems to overcome before it can be considered an effective exploration device. As stated by Iyer and Hitchcock (1976, p.821), "Even though there is considerable interest in using seismic noise in the frequency band of 1-10 Hz as a prospecting tool for geothermal energy, clear correlation between high noise levels and active hydrothermal reservoirs has been demonstrated only in a very few regions The main problem is that cultural noise and noise generated by rivers and wind are in the same frequency band as geothermally generated seismic noise and often cause confusion in indentifying the latter ground conditions can cause amplification of background seismic noise; when this occurs in a geothermal area, it is difficult to interpret a seismic noise anomaly."

In microseismology, seismic noise is monitored, usually continually at fixed stations. Although some geothermal areas have a high level of microseismic activity, microseismic surveys may be of limited value because of lack of understanding of the mechanisms involved. According to Majer and others (1976) microseismic P wave-delay surveys may be as effective a mapping tool as reflection or refraction seismology.

1. advantages:

- a. These methods utilize a natural energy source input and would be an inexpensive way to delineate structural boundaries. Reservoir activity could be continually monitored.
- b. As mentioned by Meidav and Tonani (in press) microseismic techniques can be useful in determining the gross limits of the geothermal areas, as well as defining active fault planes. By using unattended stations, microseismology can be relatively inexpensive (Duprat and Omnes, in press).

2. disadvantages:

- a. The main problem is establishing a correlation between seismic

noise anomalies and geothermal activity.

3. references:

- a. Majer and others, 1976 (microseismology)
- b. Iyer, 1975 (seismic noise)
- c. Iyer and Hitchcock, 1974 (seismic noise)
- d. Iyer and Hitchcock, in press (seismic noise)
- e. Iyer and Hitchcock, 1976 (seismic noise)

C. Gravity Method: In geothermal situations local positive gravity anomalies may develop from alteration and densification of sediments due to rising plumes of thermal water. These anomalies may be detected by standard gravimetric procedures. Gravity surveys also will detect anomalies due to a high proportion of intrusives and structural features such as faults, calderas, and basement structure. Many authors consider this a structural method with particular use in areas of smooth relief and poor geological exposure (Palmason, in press).

1. advantages:

- a. The method is economical, and measurements can be relatively easy to make in the field.
- b. Useful for detecting high density hydrothermal alteration (Hochstein, 1970, p.338).
- c. Can detect low density volcanic sediments.
- d. Can be used for deep source detection where surface conditions do not mask gradients.
- e. Effective over areas of ground cover (Strangway, 1970, p.1233).
- f. "Gravimetry has proven to be an important auxiliary exploration tool in many cases. In the Imperial Valley of California, for example, every known geothermal field is associated with measurable residual gravity anomalies", according to Meidav and Tonani (in press).
- g. Instrumentation can be used airborne.

2. disadvantages:

- a. Data from this method alone are not indicative of a geothermal area - should be used with a number of other methods such as resistivity (Meidav, 1970, p.306).
- b. Gravity data provides information primarily on structure and rock alteration.
- c. According to Duprat and Omnes (in press) this method for a 400 x 400 meter grid is about 40% more expensive per square kilometer than high-sensitivity airborne magnetometry.
- d. Interpretation of airborne data over rugged terrain can be difficult.

3. geologic considerations:

- a. Can be useful for detecting high density sediments altered by rising plumes of hot water, low density volcanic sediments, "seeing through" ground cover, and detecting structural features.
- b. As mentioned by Duprat and Omnes (in press), "Gravimetry may be used as a general reconnaissance tool for the determination of depth to basement, detection of faults, intrusions, horsts, and grabens."
- c. As successful measurements depend on good elevation control, this method works best in areas of smoothly varying relief.
- d. Instrumentation and data interpretation have been developed for lake and marine use (both surface and airborne).

4. references:

- a. Hochstein, 1970
- b. Kane and others, 1976
- c. Keen, 1968 (general - geophysics in marine environments)
- d. Meidav, 1970, p.305
- e. Meidav and Tonani, in press
- f. Palmason, in press
- g. Strangway, 1970, p.1233

D. Magnetism: Magnetism, like seismic and gravity methods, is primarily used for structural delineation. Opinion is divided on the usefulness

of magnetics in geothermal exploration work (Banwell, 1970 and Palmason, in press). Hydrothermal alteration can affect the magnetic properties of rocks and there may or may not be distinct magnetic anomalies associated with geothermal fields. Also, mapping of Curie point isotherms using aeromagnetic data may be a useful reconnaissance method for a rapid regional survey. (This techniques has been tried in Yellowstone National Park - Bhattacharyya and Leu, 1975).

1. advantages:

- a. The method can be economical for normal sensitivity instruments, and the instruments can be used airborne.
- b. This method is useful for determining thickness of sediments over reservoir and below surface structure.
- c. For structural information, airborne magnetics may be cheaper than refraction seismology. According to Duprat and Omnes (in press), ground magnetics is the cheapest ground surveying method for structural determination.
- d. May help in geologic mapping of non-outcropping hydrothermal alterations (Duprat and Omnes, in press).

2. disadvantages:

- a. A direct relationship has not been established between geothermal fluids and anomalies.
- b. Of secondary use in geothermal work - should be used with other structural methods.
- c. Data are primarily for depth determination and below surface structure.
- d. According to Duprat and Omnes (in press), "Specifications for high-sensitivity airborne magnetometry surveys are very stringent and the cost is much higher than the cost of ordinary low-sensitivity surveys. The all inclusive cost per square kilometer for a 800 x 400 meter grid may be as high as U.S. \$125.00 per square kilometer for a small survey."
- e. May be a problem with data interpretation over rugged terrain.

3. geologic considerations:

- a. As there will be no anomalies over a uniform magnetic flow, this is a good method for detecting reservoirs under a volcanic flow (Strangway, 1970, p.1234).
- b. Airborne magnetics will be a good method in areas with limited access or submerged land environments.

4. references:

- a. Battacharyya and Leu, 1975
- b. Duprat and Omnes (in press)
- c. Hochstein, 1970, p.342
- d. Kane and others, 1976
- e. Keen, 1968 (general - geophysics in marine environments)
- f. Palmason, in press

E. Heat Flow - shallow and surface measurements (up to depths of 30 kilometers): Heat flow anomalies are a general characteristic of most geothermal areas, but the measurement and detection of these anomalies presents certain problems. Heat flow by conduction is given by the relationship: $\text{Heat flow} = Q = K\Delta T$ where K is the thermal conductivity (cal/cm sec. degree C) and ΔT is the temperature gradient. (The average earth heat flow is 1.5×10^{-6} cal/cm²sec.) In order to determine heat flow at the earth's surface by conduction both the thermal conductivity and the temperature gradient must be measured. To measure the thermal gradient, probes with temperature sensitive devices (such as thermistors, thermo-couples, and thermal resistances)(Dedkova and others, 1970) are placed down a series of drill holes. Laboratory methods or an instrument such as a needle probe are used to measure the thermal conductivity from core samples.

By making a series of surface or shallow measurements of heat flow, a rapid and direct survey will be performed for a relatively inexpensive cost (compared to the expense of intermediate drill holes from 30 to 200 meters deep). (Banwell, 1970; Dawson and Dickinson, 1970; and Lachenbruch and others, 1976)

1. advantages:

- a. Fast, relatively inexpensive, preliminary surveys can be made.

This may be an effective survey method for submerged lands.

- b. This can be a good reconnaissance tool for "blind" situations with no surface manifestations.
- c. If drill holes are deep enough to eliminate seasonal and ground cover effects, data may show anomalous heat flow from reservoirs.

2. disadvantages:

- a. From surface down to certain depths, measurements will include daily, seasonal, and longer period temperature fluctuations. This is particularly relevant in marine situations due to the high heat capacity of water. Ideally, measurements should be made deep enough to eliminate these fluctuations (Lachenbruch and others, 1976).
- b. Instrumentation problems include sensitivity, long term stability, and calibration (Dedkova and others, 1970).
- c. The thermal conductivity of the material may be difficult to determine. Many shallow surveys measure gradient or bottom hole temperatures only.
- d. There is an uncertainty of hydrothermal convection processes as noted by Meidav and Tonani (in press).
- e. There can be interpretation problems because of convection, temperature fluctuations, and ground cover effects.

3. geologic considerations:

- a. According to Banwell (1970, p.41), "An almost universal overriding factor which must be taken into account when making or interpreting virtually any shallow heat flow, temperature or gradient survey, is the possible effect of movement of shallow ground water across the survey area. A relatively slow movement of meteoric water can carry away the conductive heat flow from even a strong thermal anomaly with very little temperature rise, surface temperature patterns can be displaced, and gradient measurements in deeper holes made unreliable by movements in subsurface aquifers. It is important, when planning a shallow survey, to take account of hydrological conditions in the area, including the possible rate and direction of ground water

movement, and the depth to which it may extend.". Meidav and Tonani (in press) also discuss interpretation problems due to horizontal and vertical hydrothermal convection processes.

- b. To obtain more reliable information, it may be wise to drill fewer but deeper holes for more sensitive and accurate heat flow measurements.
- c. Costs will vary greatly depending on depth of holes and terrain type. For submerged lands drilling may not be necessary and large areas can be surveyed inexpensively. (A probe should penetrate into bottom sediments.) Providing penetration is deep enough, and both gradient and thermal conductivity are measured, this can be a good general survey method for lake environments.

4. references:

- a. Banwell, 1970 (general)
- b. Blackwell and Baag, 1973 (heat flow in a "blind" area)
- c. Dawson and Dickinson, 1970 (general heat flow)
- d. Dekova and others, 1970 (instrumentation)
- e. Lachenbruch and others, 1976 (shallow and intermediate heat flow in Long Valley, California)
- f. Meidav and Tonani, in press (general critique of geophysical methods)

F. Heat Flow - intermediate depths (30 - 200 meters): The important factor in this method is the expense of drilling the holes. At these greater depths most surface effects will be removed and a more accurate and precise heat flow gradient will be established. The costs will increase greatly though, particularly in submerged land environments where drilling will now be necessary as the weight of the probe alone will not provide sufficient penetration. The heat flow data from these holes will be valuable though, and as stated by Banwell (1970, p.42), "..... measurements of temperature and gradient at a sufficient number of points in these holes can provide important

data relating to underground temperature distribution in the area. In many cases, it is probable that an array of such holes, properly distributed over the field, and supported by resistivity soundings, can supply all the information necessary for planning a deeper exploration and production programme."

1. advantages:

- a. As measurements are made over a greater depth a more accurate temperature gradient will be established.
- b. Surface effects and fluctuations will be removed.
- c. This method can give direct geothermal reservoir temperature information.

2. disadvantages:

- a. According to Duprat and Omnes (in press), "Temperature well logging is a method for direct detection of heat sources; it is a most interesting and most important one. Unfortunately it is generally expensive because significant measurements of the geothermal gradient should be carried out in homogeneous impervious formations at least 30 m deep. In the USA, a 150 m hole costs about U.S. \$3000 which is about the cost of 2 line km of refraction seismic. This cost does not include the measurement." Drilling may be more difficult and expensive for submerged lands.
- b. Accurate determination of thermal conductivity is still a problem. (Down-hole systems for measuring thermal conductivity have not been developed with success yet.)

3. geologic considerations:

- a. Terrain type will affect both drilling costs and accuracy of measurements.

4. references:

- a. Banwell, 1970 (general)
- b. Blackwell and Baag, 1973 (heat flow in a "blind" area)

- c. Dawson and Dickinson, 1970 (general heat flow)
- d. Dedkova and others, 1970 (instrumentation)
- e. Lachenbruch and others, 1976 (shallow and intermediate heat flow in Long Valley, California)
- f. Meidav and Tonani, in press (general critique of geophysical methods)
- g. Urban and others, in press (heat flow at the Geysers, California)

G. Direct Current Resistivity - including induced polarization: dc resistivity has been used extensively in geothermal exploration, and techniques and interpretation are described in a number of articles including Beyer and others, in press; Keller, 1970; Meidav, 1970; Stanley and others, 1976; Keller and others, 1975; and Zohdy and others, 1973.

A number of electrode configurations and techniques have been used, and one configuration, the bipole-dipole resistivity method with multiple stations used for large scale initial surveys is described by Beyer and others (in press) as follows, "This technique uses a controlled source, a motor-generator set capable of injecting high current (50-100 amps) into the earth through a grounded transmitting bipole which might be 1 to 3 km in length. The resultant electric field is then mapped at various locations using an orthogonal array of two short (100 m) grounded electric dipoles. An apparent resistivity for the earth can be calculated in terms of the transmitter current, the potentials across the receiver dipoles, and the location of the receiver station with respect to the transmitting bipole"

The electrode configuration or array used is an important controlling factor for survey expense, data interpretation, area surveyed, and ease of field techniques (for example bipole-dipole versus dipole-dipole array). Other arrays, such as the dipole-dipole, although more expensive, have been used with success for both large and small scale surveys.

Rock resistivities in a geothermal area are dependent upon a

number of factors. According to Stanley and others (1976): "Depending upon the geologic environment, rock resistivities in a hydrothermal system may be decreased by several orders of magnitude because of a combination of factors:

1. Increased temperature causes lowered resistivities because of increased ionic mobility.
2. Increased temperature generally causes more dissolved solids to occur in the rock fluids, lower resistivities resulting because of increased ionic concentrations.
3. Hydrothermal alteration, mainly the formation of clays and zeolites, provides higher ionic exchange capabilities.
4. Solution activity increases porosity and permeability in consolidated rocks, the rock resistivities thus being decreased. However, at the upper boundaries of a convecting system, precipitation of silicates and other dissolved solids may result in large thicknesses of an impermeable precipitate of high resistivity."

1. advantages:

- a. Can be adapted for lake and marine use (Barnes and others, 1972).
- b. Depth penetration is a function of electrode separation for a given electrode array, and deep penetration can be obtained (several kilometers) if surface layers are not too resistive.
- c. Works well for determining resistive bodies buried beneath conductive overburden.
- d. "Surface electrical methods have been successfully employed in a number of places for exploration for geothermal energy resources, because of the well known increase in electrical conductivity with temperature.", Meidav, 1970, p.303.
- e. There has been considerable work done on the interpretation of resistivity data.
- f. Can be done with both horizontal and vertical electrode configurations.

2. disadvantages:

- a. Direct current resistivity methods are best for measuring

resistive targets - the signal is stronger as resistivity increases.

- b. If a high resistivity zone is at the surface, penetration may be difficult (Keller, 1970, p.321)
- c. For deep penetration, long cumbersome electrical lines and large field crews are often necessary (depending on the array).
- d. Lateral variations in resistivity can cause interpretation problems (depending on the array).
- e. With a bipole-dipole array, Beyer and others (in press) in their work in the vicinity of Leach Hot Springs, Nevada, found a high degree of ambiguity in data interpretation, after computer modeling and field data analysis. Other arrays may not present the same interpretation problems.
- f. Resistivity depends on a number of parameters including porosity, salinity of interstitial fluid, and temperature.

3. geologic considerations:

- a. Depth penetration is limited for highly resistive surface layers.
- b. Depending on the array, because of electrical lines, equipment, and survey crews, resistivity may be a difficult method to use in inaccessible areas. (May not be a problem with bipole-dipole array - Keller and others, 1975.)
- c. The induced polarization effect will be noticeable in areas with an increased quantity of disseminated pyrite deposited by sulfur rich circulating thermal waters (Zohdy and others, 1973, p.1143).
- d. Horizontal measurements and vertical soundings down drill holes can be made (Zohdy and others, 1973 and Meidav, 1970).
- e. According to Meidav and Tonani (in press) three factors can introduce ambiguity into resistivity surveys: 1) the effect of dry steam, 2) the effect of brine, and 3) presence of clay, shale, or other highly porous but permeable rocks.

4. references:

- a. Barnes, 1972 (resistivity for use in marine situations)
- b. Beyer and others, in press (bipole-dipole resistivity and other electrical methods)
- c. Keller, 1970 (general)
- d. Keller and others, 1975 (bipole-dipole resistivity)
- e. Meidav, 1970 (resistivity and gravimetry)
- f. Stanley and others, 1976 (deep electrical investigations)
- g. Zohdy and others, 1973 (resistivity, self-potential, and induced polarization)

H. Inductive Methods - excluding tellurics and magnetotellurics: As stated by Keller (1970, p.321), "Earth resistivity can be measured inductively a great many ways. In essence, though, an inductive method consists of generating a magnetic field which varies in time, and detection of either the electric field or the magnetic field arising from the currents induced in the earth.". There are four types of sources for the time varying magnetic field: 1) a magnetic dipole, 2) a short current dipole, 3) a long (infinite) current dipole, and 4) the natural magnetic field of the earth. Both frequency domain measurements and time domain measurements can be made. At the receiver one or two components of the electromagnetic field are measured, and these may be separated into components which are in phase and out of phase with the current to the source.

1. advantages:

- a. Depending on the type of equipment, this can be a relatively easy method to use in the field.
- b. This is an effective method for use at shallow depths (50 meters) in rugged terrain.
- c. "Perhaps the greatest advantage of inductive methods is that measurements may be made through highly resistant surface rocks with little or no screening effect.", (Keller, 1970, p.332).

- d. "A two-coil moving source-receiver arrangement (electromagnetic gun) has been used in New Zealand and Chile to map shallow resistivity profiling, because of its low cost and high speed. The field procedure is straightforward, and apparent resistivities are obtained from calculated curves." (Palmason, 1976).
- e. This method may be less affected by lateral inhomogeneities than some dc resistivity soundings.
- f. Barnes and others (1972, p.23) describe equipment and techniques for surveying in submerged land environments.

2. disadvantages:

- a. Depth penetration may not be great depending on the type of equipment and the distance between transmitter and receiver.
- b. As with all electrical methods, there are noise problems, including those from man made sources.

3. geologic considerations:

- a. This is a good method to use for shallow resistivities for initial surveys in areas with rugged terrain (Banwell, 1970, p.54).

4. references:

- a, Banwell, 1970 (general)
- b. Keller, 1970 (specific methods)
- c. Barnes and others, 1972 (marine techniques)
- d. Lumb and MacDonald, 1970
- e. Palmason, in press (general)

I. Self-Potential: Electrical potential anomalies may be generated in geothermally active areas either through thermoelectric coupling or by the generation of streaming potentials caused by the motion of sub-surface fluids (cation enrichment of the water takes place by preferential absorption of the anions by the rock). These anomalies, usually in the order of tens of millivolts, generally are positive for ascending waters and negative for descending waters. (Potential

increases as high as 1100 millivolts around the perimeter of the Long Valley caldera have been reported by Anderson and Johnson, 1976, p.1527.) Measurements are made by a simple two non-polarizing electrode array and a potential measuring device. Because of several noise sources, careful field techniques are required, and data interpretation may be difficult (Corwin, 1973 and 1976).

1. advantages:

- a. The instrumentation is simple and inexpensive compared to other geochemical and geophysical methods.
- b. A field survey can be done with one or two people in a relatively short period of time.
- c. Field techniques are easily adaptable for exploration work in submerged land environments (Corwin, 1973). This may be the simplest and most inexpensive geophysical method to use in this type of situation.

2. disadvantages:

- a. There are a number of factors which will influence data quality including telluric currents, electrode effects, and survey techniques (Corwin, in press)
- b. Careful field techniques are a necessity in areas where geothermal self-potential anomalies have low amplitude and long wave length.
- c. "Tie-ins" during a field survey can result in cumulative errors (Corwin, in press).
- d. Self-potential is an electrochemical phenomenon due to a number of causes, some of which are unrelated to the convection of hot geothermal fluids (Meidav and Tonani, in press). An absolute correlation has not been established between anomalous surface potentials and thermal sources at depth (Anderson and Johnson, 1976, p.1527).

3. geologic considerations:

- a. Because of the size of geothermal reservoirs, a survey may

have to be done over several kilometers.

- b. Ground cover composition and conditions will affect the data quality.
- c. This method may be effective for submerged land surveys.

4. references:

- a. Anderson and Johnson, 1976 (self-potential in Long Valley, California)
- b. Combs and Wilt, in press (telluric and self-potential)
- c. Corwin, 1973 (specific on self-potential)
- d. Corwin, in press (specific on self-potential)
- e. Zohdy and others, 1973 (resistivity, self-potential, and induced polarization)
- f. White and others, 1964 (self-potential survey)

J. Telluric and Magnetotelluric Methods - including tellurics, magnetotellurics, and audiomagnetotellurics:

a. Tellurics: "The telluric method makes use of a naturally occurring electromagnetic field, generated by variations of the magnetic field of the planet, and associated telluric currents induced by them in the ground. In general, the telluric method consists of measurement of spatial variations in the electric field and subsequent interpretation in terms of lateral variations in the electrical properties of the subsurface." from Combs and Wilt (in press).

b. Magnetotellurics: Most magnetotelluric measurements are made at very low frequencies (less than 0.06 Hz) providing penetration into the earth to tens of kilometers (Keller, 1970, p.329). "In a magnetotelluric determination of earth resistivity, one measures the simultaneous magnitude of orthogonal horizontal electric and magnetic field components. By assuming that these components belong to a plane wave propagating vertically into the earth, the earth resistivity can be computed from the formula", from Keller (1970, p.330).

c. Audiomagnetotellurics: As stated by Keller (1970, p.329), "Of more value perhaps, in reconnaissance for geothermal areas, is

the so called audio frequency magnetotelluric method (the AMT method) which makes use of the natural noise in the frequency range from about 8 Hz to as high as 20k Hz. The natural electromagnetic field at frequencies above 8 Hz is contributed by induction from power distribution systems and by energy from atmospheric electric discharges". "Basically, the electromagnetic impedance - the ratio of the horizontal electric field (E) in the ground to the orthogonal horizontal magnetic field (H) - is measured at a number of frequencies - resulting in a form of depth sounding. Operationally the technique is quite simple in that depth sounding is conducted by making measurements at only one location.", from Strangway and others (1973, p.1159).

1. advantages:

a. tellurics:

- 1) The methods described by Beyer and others (in press) may be more economical and employ less field equipment than some traditional electrical methods. Generally a crew of two can make a survey.
- 2) Less complex than magnetotelluric methods as the magnetic field is not measured.
- 3) All tellurics take advantage of the natural sources for the energy source.
- 4) Deep penetration can be obtained without long cumbersome electrical lines or large field crews.

b. magnetotellurics:

- 1) Very deep penetration into the earth because of low frequencies.
- 2) As with tellurics, this is an easy field method to use.
- 3) By combining tellurics and magnetotellurics, it is possible to make pseudosections of apparent resistivity

c. audiomagnetotellurics:

- 1) The method emphasizes conductive, not resistive, bodies such as are commonly associated with hot water and alteration zones. Will tend to look through high resistivity materials

(Hoover and others, 1976).

- 2) Simplicity of equipment and survey methods are an advantage compared to other electrical methods.
- 3) A survey crew of two men can be used. Depth soundings can be made from one location.

2. disadvantages:

a. tellurics:

- 1) As with all telluric methods, true resistivities of the subsurface are not given. (With magnetotelluric calibrations, pseudosections of apparent resistivity are possible.)
- 2) This method does not give detailed electrical structure.
- 3) For all telluric methods noise will occur from cultural (man made) electrical sources such as power lines.
- 4) The energy source of natural fields may be unreliable.
- 5) The survey line direction is proscribed by the telluric field direction.

b. magnetotellurics:

- 1) Unlike tellurics, the magnetic component also must be measured. The instrumentation will not be simple.
- 2) Because of great depth penetration, there is an insensitivity to shallower resistivity variations (Palmason, in press).

c. audiomagnetotellurics:

- 1) Large errors in depth estimation can occur due to very poor resolution of intermediate high resistivity beds.
- 2) Due to energy sources, there will be some data scatter and data non-repeatability.
- 3) Noise will occur from various man made sources such as power lines.
- 4) Cannot be used where there is conductive over-burden.

3. geologic considerations:

- a. For all tellurics two assumptions are made: 1) that the primary telluric field is spatially constant over large areas, and

that 2) the field be a steady state dc field with no displacement current (Combs and Wilt, in press). The method is mainly suitable for mapping horizontal resistivity variations.

- b. Magnetotellurics are useful primarily for deep resistivity delineation because of low frequencies used.
- c. Audiomagnetotellurics operate effectively in areas of highly resistive surface areas as the conductiveness of material is measured - good surface and depth penetration.
- d. Audiomagnetotellurics are of little use in looking for zones buried beneath conductive over-burden (Strangway and others, 1973, p.1174).
- e. "Present experience indicates that the telluric profiling method may be useful in regional surveys, and that the audio-frequency magnetotelluric method may be very convenient in more detailed work.", from Palmason (in press).
- f. Telluric methods might be adaptable for use in submerged land environments. Magnetotellurics, because of the low frequencies, might be the most effective technique - the higher frequency signals of tellurics and audiomagnetotellurics could be attenuated by the conductive water layer.

4. references:

- a. Beyer and others, in press (comparison of telluric and resistivity methods)
- b. Hoover and others, 1976 (audiomagnetotellurics)
- c. Keller, 1970 (various telluric methods)
- d. Palmason, in press (general methods - comparison)
- e. Strangway and others, 1973 (audiomagnetotellurics)

K. Remote Sensing Techniques: These techniques include:

- 1) microwave radiometry (wave length in the 1 centimeter range)
- 2) thermal infrared imagery (wave length from 8-14 microns)
- 3) black and white photography multiband (visible spectrum - 0.4

to 0.9 micron range).

4) color photography and infrared color shift photography

These are primarily airborne techniques used at heights from 300 meters to 3000 meters depending on whether the data is for detailed mapping or for general reconnaissance work. The photographic sensors (visible and infrared) are usable only in the daytime to detect anomalies associated with the reflection of incident sunlight. The photographic sensors and thermal infrared techniques will make measurements of only the first few microns of surface material, and thus are useful primarily for surface effects. Photographic infrared has no relationship to actual temperature except for use with incandescent bodies, while thermal infrared can directly detect surface temperature anomalies by sensing anomalous heat flow to the earth's surface. In theory microwave measurements represent the integrated temperature of the surface layer with a non-negligible thickness, and therefore could be used for depth temperature measurements. The "state of the art" (1970) microwave relative sensitivities are in the range of 1 to 3 degrees K, and for thermal infrared on the order of 0.5 degrees K (Hodder, 1970, p.370). New techniques are being developed which should have greater sensitivities for relative temperatures and heat flow (Del Grande, in press).

1. advantages:

- a. Remote sensing techniques might be used as a replacement for detailed more expensive, surface and shallow temperature surveys.
- b. These techniques can be an effective method for monitoring the total geothermal field.
- c. According to Duprat and Omnes (in press), "..... a large area can be surveyed in a relatively short period and the cost of flying, recording, and converting the taped signals to pictures does not exceed U.S. \$10.00 per square kilometer for regional surveys.". This could be an effective method for an initial survey or light reconnaissance of a large previously unexplored geothermal area.

- d. Depending on the extent of thermal mixing, these techniques may be used for airborne surveying of heat anomalies from submerged land.

2. disadvantages:

- a. Most techniques will measure only surface conditions. There can be interpretation problems with the data because of radiation masking heat flow through conduction.
- b. Effects of vegetation and diurnal variations will cause additional interpretation difficulties. To eliminate some of these effects, surveys are often made at pre-dawn in order to let the top few centimeters of soil come into thermodynamic equilibrium.
- c. Most infrared techniques, under all but ideal conditions, have a heat flow sensitivity of only about 100-500 times the global average (global average heat flow - approximately $1.5 \times 10^{-6} / \text{cm}^2 \text{sec.}$) (Del Grande, in press).

3. geologic considerations:

- a. Because of the lack of depth penetration, remote sensing techniques may be best applied for the detection of surface or near-surface manifestations in areas where access is difficult (Duprat and Omnes, in press).
- b. Hodder (1970, p.376) reached these conclusions after a survey of six areas in California:
 - Passive microwave radiometry in proximity to the water vapor band (e.g. 19.5 GHz) is effective in daytime identification of surface seeps that are not detectable as geothermal areas because of their intrinsic heat.
 - Nighttime infrared and microwave radiometry correlate in indicating high temperatures for known geothermal areas (high measured heat flow).
 - Color infrared photography is sensitive primarily to vegetation anomalies and may be used to separate vegetation effects in the thermal infrared data imagery.
 - Thermal areas in a variety of geologic settings seem acces-

sible to identification and mapping by these techniques even in the absence of a surface seep."

- c. As both thermal infrared and microwave reflect near surface moisture conditions, they can be used to look for contrasts in moisture content, indicating fault zones.
- d. Mid-day thermal infrared is also useful to compare with pre-dawn thermal infrared, to detect contrasts in composition of near surface soil or rock; differences in thermal inertia of different materials may give diagnostic patterns on imagery.

4. references:

- a. Dawson and Dickinson, 1970
- b. Del Grande, in press
- c. Duprat and Omnes, in press
- d. Hodder, 1970

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A GEOTHERMAL PROSPECTING HEAT FLOW
SYSTEM
for
THERMAL GRADIENT
and
THERMAL CONDUCTIVITY MEASUREMENTS

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PREPARED August 1976

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I INTRODUCTION AND PURPOSE OF INSTRUMENTATION

The instrument and data handling and operational procedures described herein are for a geothermal prospecting tool designed to meet the needs and requirements of the California State Lands Commission to aid in the initial assessment of the geothermal potential of the submerged lands under the jurisdiction of the State of California. In the fall of 1975, members of the staff of the State Lands Commission met with research workers from the Energy and Environment Division of the Lawrence Berkeley Laboratory of the University of California to discuss a possible joint program in which the staff of the State Lands Commission would actively participate in a preliminary assessment of the geothermal potential of state owned submerged lands utilizing the experience and expertise of the Lawrence Berkeley Laboratory. The major considerations were that any field programs (1) be conducted by State Lands personnel, (2) with equipment built by LBL, but (3) operated by State Lands, (4) from a small boat, (5) measuring a useful but significant geothermal parameter, (6) in a field program that must be completed by 1 June 1976.

It was agreed that the best way to meet these requirements was to make heat flow surveys in the surficial sediments of the bottoms of at least three lakes using a modification of the conventional oceanographic heat flow probe unit.

The modifications include not only major changes in the recording of the thermal data on-deck but also use of new materials for the probe and an innovative technique to measure the thermal conductivity in place in the bottom sediments. As such changes make the unit designed by LBL in co-operation with the State Lands Commission significantly different from the standard oceanographic heat flow probe a complete description is given in the following sections not only of instrumentation but also of its operation.

THEORY OF OPERATION

II. INTRODUCTION

Heat flow occurs in three modes - conduction, convection, and radiation. Radiation is negligible near the earth's surface. Conduction is by far the most important mode of heat flow, and is frequently assumed to be the only mode involved in the near-surface regions of the earth. However, convection mode heat flow, due to ground water movement in rocks or sediments, does occur, and in many regions is the primary mode of heat flow.

Verhoogen, et al. (1970, pp. 637-661) present a good introduction to heat flow and the thermal history of the earth. The primary sources of energy for geothermal heat flow are radioactive decay of elements and residual heat from the earth's formation some 4.5 billion years ago. The average heat flow from the earth is somewhat over 10^{-6} cal./cm.²-sec; however, large variations in heat flow are observed on a global scale. Precambrian shields and ocean trenches show lower than average values, while mid-ocean ridges and tectonically active areas on continents show higher values. Volcanic and other geothermally interesting areas of primary concern in this project can show much higher heat flow than normal.

The mathematics governing conductive heat flow is contained in the following two equations from Carslaw and Jaeger (1959, p. 8 and 10):

$$(1) \quad \Delta^2 T - \frac{1}{D} \frac{\partial T}{\partial t} = - \frac{A}{K}$$

$$(2) \quad \bar{q} = -K (\Delta T)$$

Symbols are defined as follows:

T = temperature in °C

t = time in seconds

K = thermal conductivity of medium in cal/cm - sec - °C

q = heat flow vector in cal/cm² - sec.

A = heat source density in cal/cm³ - sec.

D = thermal diffusivity in cm²/sec. = K/volumetric specific heat of medium Equation (1) governs temperature as a function of time and position. Equation (2) relates heat flow to the temperature of the medium. These equations assume that K and D are not functions of temperature, and that the medium is isotropic, i.e. $K_x = K_y = K_z$, etc. In cases where these two assumptions cannot be made, the mathematical difficulty increases, greatly reducing the number of problems one can effectively solve. Appropriate simplifications can be made to the equations according to the physical situation one is interested in.

To model heat flow near the surface of the earth exactly is impossible; hence approximations are made to produce a simple model, then the errors introduced by the approximations are examined. The following assumptions are made:

- (1) No heat is being generated in the area of interest ($A = 0$).
- (2) The surface of the earth can be represented by an infinite plane in the x and y directions, held at some fixed temperature.

- (3) Heat from a hotter region below (in the positive z direction) is flowing up to the surface uniformly over the entire region; i.e., there is only vertical heat flow.
- (4) The medium below the surface has uniform isotropic thermal conductivity K.
- (5) This situation has existed long enough for an equilibrium to be established; i.e., there is no change of temperature with time. With all these assumptions, equation (2) reduces to q equals a constant value independent of position as shown below:

$$q = -K \frac{T_2 - T_1}{z_2 - z_1}$$

Where T is the temperature and z is the vertical distance of a given point below the earth's surface. Heat always flows toward the surface with the assumptions.

Heat flow measurements thus involve two measurements at any site - the thermal conductivity K, and the difference in temperature between two points separated by a known vertical distance. Multiplied together, these two quantities yield the heat flow at the site.

Temperature Gradient Measurements

The temperature measurements for the State Lands probe are made in two ways. The first is a direct measurement of voltage drop across the thermistor, along with the voltage applied across both the thermistor and a precisely known fixed resistor. These two voltages are shown as V_0 and V_T in Figure 2 below.

Figure 2

F is the resistance of the fixed resistor. R_T is the resistance of the thermistor, shown inside the circle on the diagram. To find R_T , we apply Ohm's Law to the circuit.

$$I = \frac{V_T}{R_T} = \frac{V_0}{R_T + F}, \text{ Hence } R_T = \frac{F V_T}{V_0 - V_T}$$

Having obtained the resistance for the thermistor, we obtain the temperature from the equation:

$$T(^{\circ}\text{C}) = \left(\frac{1}{\alpha + \beta \ln R_T + \gamma (\ln R_T)^3} \right) - 273.16$$

The parameters α , β , and γ are determined for each thermistor by precise laboratory measurements of resistance at several different temperatures. This function is approximately the inverse of the resistance function for an ideal thermistor, namely $R_T = C \exp(B/T(\text{absolute}))$.

A more precise method of obtaining relative temperatures with respect to one of the thermistors (T-2 for these probes) uses an unbalanced Wheatstone bridge having two precisely known fixed resistors for two legs, thermistor T-2 for the third leg, and the other thermistor for the fourth leg, as shown in Figure 3 below.

Figure 3

F_1 and F_2 are the fixed resistances, while R_1 and R_2 are the thermistor resistances of the i th thermistor and the reference thermistor T-2, respectively. V_2 is the direct mode measurement for thermistor T-2 discussed earlier. Again applying Ohm's Law:

$$V_i = I_i R_i = \frac{R_i V_0}{R_i + F_i}$$

$$V_T = V_i - V_2 = \frac{R_i V_0}{R_i + F_i} - V_2$$

$$\text{Hence } R_i = \frac{(V_T + V_2) F_i}{V_0 - (V_T + V_2)}$$

The advantage of this method is that the voltage V_i is always small enough to be measured on the most sensitive scale of the digital voltmeter used with the probe.

In both direct mode and bridge mode measurements, the voltage applied to the fixed resistors and the thermistors is kept to about 0.4 volts, a compromise between larger measured voltages to give better accuracy, and the problem of self-heating of the thermistors due to the current passing through them. Appropriate switches are included in the circuitry to allow measurement of applied voltage, direct mode measurements across all six thermistors, and bridge mode measurements of all thermistors except the reference thermistor T-2. In addition, the cable resistance between probe and instrument box can be measured to correct for changes due to temperature variation.

THERMAL CONDUCTIVITY MEASUREMENTS

Standard methods of thermal conductivity measurement include the steady state technique for laboratory use discussed by Ratcliffe (1960), and various "needle probe" arrangements utilizing the temperature rise vs. time curve for a long cylindrical heat source, such as the apparatus described by Von Herzen and Maxwell (1959). The needle probe technique has been adopted for in situ measurements by Sclater (1969) and others. It has several faults; power consumption is relatively high, the probe is fragile, and measurements are made only in the upper quarter meter of sediment. Lister (1970) has done some work using the temperature gradient probe itself as a heat source for thermal conductivity measurements, which eliminates the last two problems but requires much higher power consumption and a longer measurement time.

The self-heating technique of thermal conductivity measurements was developed to solve these problems. Suggested by the Fenwall Thermistor Manual (1974), this technique utilizes the self-heating which occurs in the thermistors when current passes through them. Each thermistor is potted in epoxy close to the surface of the fiberglass probe rod. When heated, a thermistor can be approximated by a point source of heat on the surface of a half-space corresponding to the sediment surrounding the rod. Sediments of higher thermal conductivity will conduct heat away from the thermistor better than lower conductivity sediments. If all other factors are the same, the resulting temperature rise will be lower in the sediment having higher thermal conductivity.

The temperature of each thermistor before heating is already known from the temperature measurements made to obtain the thermal gradient. To measure the rise of temperature with time and the amount of heat being dissipated in each thermistor, a procedure almost identical to that described with Figure 2 is used. Input voltage and voltage drop across the thermistor are measured, and the same expression for R_T is still valid. The difference is the use of a much higher input voltage - approximately 13 volts instead of the 0.4 volts used for temperature gradient measurements. As heat dissipation is proportional to the square of the voltage across a resistance, this voltage increase causes a corresponding heat dissipation increase of about 1000 over the gradient measurement heat dissipation. The associated thermistor temperature rise is between 2 and 12 degrees C, depending on the individual thermistor and the sediment around it. Power dissipation per thermistor is 5 to 10 milliwatts.

Analytical solution of temperature rise vs. time is impossible because of the thermistor shape, its placement at some depth below the surface of the fiberglass rod, and the effect of the steel strength member surrounding the rod. Consequently, calibration of each of the five thermistors in a rod is necessary for thermal conductivity measurements. By comparing field data with a set of calibration curves, a reasonable value for thermal conductivity should be obtained for the sediment at the measurement site. This calibration work is still in progress, as described in Appendix "A". The common oceanographic procedure of using an assumed value of thermal conductivity for heat flow computation has been used in the meantime.

Accuracy

Various factors, either natural or instrument related, can cause errors in the final heat flow value obtained at a specific point. First is the limitations of the electronics, and the sensitivity of the digital voltmeter in particular. The voltmeter used for this survey had a 10 microvolt sensitivity on the most sensitive voltage scale, which ranged from 0 to 200 millivolts. The 0 to 2 volt scale used for applied and direct voltage measurements had a 0.1 millivolt

sensitivity. For a typical 5 kilo-ohm thermistor (measured at 25° C) making a measurement at 15° C., a 0.1 millivolt error in both applied and direct mode thermistor voltage, plus a 0.1 ohm error in the value of the fixed resistor, can cause a maximum error in temperature of about 0.04° C. Calibration errors vary between thermistors; most thermistors have maximum errors of between 0.01 and 0.02° C. Consequently, 0.05° C. is a reasonable choice for the maximum expected error in temperature at 15° C. For other temperatures, the expected error will not change much.

For bridge measurements, the extra accuracy of the 10 microvolt scale gives temperature errors due to instrumentation of only 0.002° C., relative to the reference thermistor. However, because each thermistor has its own absolute temperature calibration, the temperature difference is only accurate to the combined calibration accuracy of the two thermistors in question. Better calibration accuracy is desirable for future probe construction, either by selection of the most accurately calibrated thermistors, or by use of more sophisticated calibration techniques.

Nonvertical entry causes an error in the heat flow value of a site because of the assumption that the vertical spacing between thermistors equals their spacing on the probe rod. The effect is to lower the observed heat flow below the actual heat flow by a factor corresponding to the cosine of the angle between the rod and the vertical. The angle must exceed 8° to cause a 1% error, and must exceed 25° to cause a 10% error in the thermal gradient and heat flow. Because the probe has a center of gravity much below the suspension point, the angle in soft sediments, for which the probe was designed, should be unimportant unless the probe is deflected by striking a rock or other hard object upon penetration.

Time between probe penetration into the sediment and temperature measurement involves consideration of three factors. First is the time required for dissipation of the probe's kinetic energy of descent, which is converted to heat upon penetration. Second is the time required for the probe to reach thermal equilibrium with the surrounding sediment. Third is the time after which the more thermally conductive steel strength member begins to distort the thermal gradient. Discussions of these problems are given by Jaeger (1956), Bullard (1963), and Lister (1970). In this survey, the problem of the penetration heat dissipation is much less because the probe is slowly lowered into the sediment instead of impacting with a velocity of two or more meters per second. However, the use of the thermally insulating fiberglass rod means a longer time for establishment of an equilibrium with the sediment. The complicated geometry of fiberglass surrounded by steel also complicates the mathematics. Further study of this problem is advisable for future work; the 10 to 15-minute waiting period might be lengthened, or an infinite time temperature estimation might be used as discussed by Lister (1970).

Errors in the thermal conductivity measurements cannot be estimated until completion of the laboratory calibration. An accuracy of 10% would be quite acceptable.

Natural errors also affect the accuracy of heat flow measurements. The most important in this survey is the effect of annual bottom water temperature variations propagating into the sediment. Carslaw and Jaeger (1959, p. 67) give the equation for the ideal case of a sinusoidal annual temperature variation, which is exponentially attenuated with depth. Although the results depend on the thermal conductivities of the sediments involved and the size and shape of the annual temperature variation, it is clear that this heat flow greatly exceeds the geothermal heat flow in the upper two meters of sediment under most conditions. Using an assumed sinusoidal temperature variation of 22.5° C. in the Salton Sea, heat flow values of over 100 times the earth's average can be expected at a depth of one meter. The sign of this heat flow can be either positive or negative, i.e.,

towards or away from the bottom, depending on the time of year. This makes the normal geothermal heat flow impossible to see; however, techniques for extracting much higher heat flow values associated with geothermal regions may be feasible. Good data about water temperature over several years at various locations and depths in a lake would be helpful by allowing accurate calculation of this annual heat flow, which could then be subtracted from the observed heat flow to yield the geothermal heat flow. More work on this problem is essential for future surveys.

Other effects can be important, although no attempt was made to correct for them in this survey. Lachenbruch (1957) discusses the problem of horizontal temperature gradients and resulting distortion of ideal vertical heat flow. Lachenbruch and Marshall (1966) present an excellent summary of a large variety of other natural causes of anomalous heat flow values, including topographic relief, transient effects of sedimentation and ocean circulation, radioactive heat, effects due to variations in the thermal conductivity of rocks, phase changes, convective heat flow, and tectonic motion. Von Herzen and Uyeda (1963) discuss some of the same effects. Especially near the shorelines of lakes, we can expect the effect of both sedimentation rate and types of sediments to be important. Also worth noting in the paper by Lachenbruch and Marshall (1966) is a departure from the empirical relationship between water content and thermal conductivities of ocean sediments noted by Bullard (1963). This departure may affect indirect thermal conductivity determinations by water content measurements, especially when the wider variety of lake sediments compared to ocean sediments is considered.

III DESIGN CHARACTERISTICS

The prospecting device required for geothermal investigations of the State of California's submerged lands differs significantly from presently used oceanographic heat flow probes. The major differences are as follows:

<u>OCEANOGRAPHIC PROBE</u>	<u>LBL-STATE LANDS PROBE</u>
two thermistors on rod probe, outrigger type attach to core barrel may have more all stainless steel	six thermistors, five on probe, one in the water
self-contained recording package, no on-deck read-out	stainless steel outer jacket, internal fiberglass tube - cut-out of stainless at thermistors exposing fiberglass
single strain cable connection between probe unit and surface	on-deck read-out with interrogation of thermistors controlled by operator
heavy, over several hundred pounds, must be raised and lowered with powered winch	two cables: stain cable to on-deck winch, and electrical cable to on-deck read-out
thermal conductivity estimated or extrapolated by needle probe measurement of collected bottom sample	relatively light up to about 50 pounds, can be lifted by one person, raised and lowered by hand-cranked winch
weight essentially fixed by combination of probe and pressure case	thermal conductivity measured in place in vicinity of each thermistor
probe and pressure case single unit	weight may be trimmed by adding or subtracting slotted weights on the weight stand
	probe may be detached and exchanged

The fundamental differences are due to the operational requirements of the State Lands Commission, that is, the unit must (1) must be operated from a trailerable boat on (2) lakes rather than the open ocean. The small boat requirement immediately limited the weight of the total unit to that handled by muscle power, which in turn eliminated the conventional on-bottom automatic control and read-out that requires a heavy pressure case. The weight and the distribution of the weight was a delicate problem as the probe unit had to be sufficiently heavy to allow maximum vertical penetration, but light enough so that the unit could be extracted from the bottom by muscle power through a mechanical winch. None of the weight factors are practical considerations in an oceanographic heat flow probe where oceanic operations demand a ship of sufficient size to have power driven winches and other labor-saving devices. The weight limitation also restricted both the diameter and the length of the penetrating probe. We chose as a first try a one meter probe of Nema grade G-10 fiberglass .5" OD with a .125" wall thickness. This initial probe worked satisfactorily in soft lake sediments of the Salton Sea, but was not suitable in sandy sediments where maximum penetration was not obtained. In this case the bottom unit acted like an upside-down pendulum and the flex strength of the fiberglass was exceeded. Accordingly the first probe fractured at the fourth thermistor. To avoid excessive flexing and to add additional strength the second generation of probes were clad inside a #304 stainless steel tube .625 OD X .028" wall thickness. This stiffening proved satisfactorily for measurements in both Clear Lake and Mono Lake. To permit thermal conductivity measurements the stainless steel was cut-out at each thermistor and a sylastic coating was applied on either side of the cut-out to thermally isolate the thermistor from the stainless steel. Ideally the sandwich should be reversed with

with the stainless steel clad by fiberglass. However the time constraints of the delivery dates of needed parts and the fixed schedules of field operations prevented construction of this modification.

The spacing of the thermistors also is different from that normally used in oceanographic heat probes. In the oceans sedimentation rates are generally much lower and the sediments in a given area more uniform than found in lakes. The thermal regime of the ocean particularly near the bottom is more stable than that of lakes and is not effected by seasonal changes as are lakes. The combination of greater variability in the ambient thermal regime and in sediment types in lakes suggest that the wide vertical spacing between thermistors found in oceanographic probes could give misleading thermal gradients if used in lakes. We chose a 20 centimeter spacing of five thermistors to give four thermal gradients at various depth instead of one gradient overall as used in conventional Bullard type probes. This is to avoid no-data stations if the probe did not penetrate completely. The seasonal effects on the ambient thermal regime in the bottom of lakes indicate the gradients of the upper pairs are not as useful as are those from the lower (deeper) pairs. However as noted in the theoretical section, the length of the probe required to penetrate beyond the seasonal effect is much too great for any probe unit hand-launched and recovered from a small boat. The primary goal of the project, fortunately, was not to measure terrestrial heat flow but to prospect for potentially commercially attractive geothermal areas. The heat flow from a commercial area by nature must be higher than normal. Accordingly the signal from an anomalous geothermal area of commercial size should be larger than the "noise" generated by seasonal fluctuations of the surface and near-surface temperature regime. To efficiently accomplish this, however, the seasonal ambient regime should be calculated for the time of year of the measurements and treated as the background level.

IV PHYSICAL DESCRIPTION

The complete prospecting heat flow unit consists of six basic segments: (1) the probe rod connected to (2) the weight stand; (3) a stainless steel strain cable connecting the weight stand to a winch on the boat; an electrical cable connecting electrical wires from the thermistors on the probe passed through the weight stand to the monitoring box on the boat; and (6) a digital multimeter read-out connected electrically to the monitoring box.

A. THE PROBE ROD

The probe rod is a 48.6" length of stainless steel sheathed fiberglass tube containing five thermistors. The fiberglass tube is NEMA grade G-10 with .500" OD X .125" wall thickness. The fiberglass tube is sheathed by a #304 stainless steel tube .625"OD X .028" wall thickness bonded to the NEMA tube by epoxy. The five thermistors are spaced 20 centimeters apart starting five centimeters from the 2.75" stainless steel tip end. Details of the mounting of the thermistors are shown in figure 4. Each thermistor on the rod is set in a cast epoxy sleeve which is epoxy-bonded to the fiberglass rod. The electrical leads for the thermistors are faired through the hollow center of the fiberglass tube to a 10 pin connector at the blunt end of the probe. In operation the probe is attached to the weight stand and the interior of the probe filled with silicone oil to increase the water-tight integrity and to reduce thermal-electric noise in the lead wires.

B. THE WEIGHT STAND

The weight stand provides electrical and mechanical connection between the probe rod and the electrical and strain cables, serves as the mount for the thermistor reading the near-bottom water temperature, and as the base for up to six weights of two kilograms each required as added mass to aid in penetration of the bottom. The mechanical arrangement of the components of the weight stand are given in figure 5.

C. THE ON BOTTOM UNIT - PROBE/WEIGHT STAND COMBINATION

During field operations the probe and the weight stand are rigidly attached together. The combined unit has a length of 67.5" (171.45 centimeters) and weighs 4 kilograms without the attached weights. With all six weights attached the total weight of the on bottom unit is 16 kilograms. In the field the combined unit can penetrate to a maximum to the base of the plate of the weight stand. Thus at maximum penetration thermistor T 1 is 137.95 centimeters below the water-sediment surface and the upper thermistor T 5 at 57.95 centimeters below the water-sediment surface. For reasonably stiff sediments, penetration is to the base of the lowest weight so T 1 would be 128.4 centimeters and T 5, 48.4 centimeters below the sediment surface.

D. STRAIN CABLE

A stranded stainless steel cable attached to the bridle of the weight stand provides positive connection between the on bottom unit and the boat. This cable is normally part of the boat's winch and left on the winch drum. It may be of any size convenient for winch operation and capable of raising and lowering the on bottom unit and withstanding its pull-out force from the bottom.

E. ELECTRICAL CONDUCTOR CABLE

Electrical connection between the thermistors on the probe/weight stand unit is provided by a neoprene coated shielded 12 conductor cable with (1) an underwater connector at the end attached to the weight stand and (2) a normal connector which connects to the Monitor box at the boat end. This cable is not designed to take the strain of the weight of the strain cable and the on bottom unit and thus should be slack mounted at all times. The electrical cable is stored on a drum separate from the boat's winch drum.

FIG. 4
THERMISTOR IMPLANTMENT DETAILS
1:4 SCALE

FIG. 5

HEAT FLOW PROBE

1:2 SCALE

F. MONITOR AND CONTROL BOX

The Monitor box contains the electronics, battery operated power supply and interrogation switches needed for both temperature (thermal gradient) and thermal conductivity measurements. The package is housed in a water-proof Zero model Centurion Elite 100-X aluminium case 9"x12"x5". The 14 pin connector labeled PROBE in figure 6. mates the boat end of the electrical cable to the electronics of the Monitor box^(see Fig. 1). The panel of the face plate of the Monitor is shown in figure three.

G. DIGITAL MULTIMETER READ-OUT

Digital values of voltages and resistances in response to the controls of the Monitor box appear on the display of a Valhalla model 4400 Digital Multimeter, which also is transported in a Zero model Centurion Elite 100-Z aluminium case. The Valhalla is connected to the voltmeter jacks of the Monitor box via a two-conductor cable with banana plugs at each end. The face plate containing the display and the mode switches plus the input jacks are shown in figure 7. The Valhalla has its own power supply independent of the Monitor box. Instructions for Valhalla are found in the company supplied manual stored inside the unit. Access to the manual and to the batteries and electronics is by removing the plastic top of the unit by slipping the four side locking latches.

VOLTMETER

DIFF
BRIDGE

FIG. 6
MONITOR BOX PANEL LAYOUT
(APPROX.)

POWER SUPPLY

LOW VOLTAGE
ADJUST

THERMISTORS

READ
PWR SUP

PROBE

1 AMP

1"

FIG. 7
DIGITAL MULTIMETER PANEL
(VALHALLA 4440)

V. ASSEMBLY

1. Hold on edge circular plate.
2. Insert washer and hexagonal threaded bolt into one of the holes on the outer perimeter of plate from the side with the shortest piece of welded bushing.
3. Attach leg piece of hexagonal stock to threads protruding through hole.
4. Tighten so that leg and longest part of welded bushing are on the same side.
5. Repeat steps (2)-(4) alternating holes used so the three legs form a triangle. The three legs attached to the plate form the weight stand.
6. Place the weight stand on its legs and the short side of the welded bushing up.
7. Insert from the underside of the plate the eyebolt, with the bridle wire attached, through one of the remaining holes on the outer perimeter of the plate.
8. While holding the eyebolt against the plate, place washers and the nut on the upward protruding threads-tighten against the plate.
9. Repeat steps (7)-(8) for remaining two eyebolts and attached bridle wires. Free ends of bridle wires should hang below the plate and the legs and eyebolts should alternate in position around the rim of the plate.
10. Gather together loose ends of the bridle wires. Pass the swivel through the made-up eyes first insuring that the bridle wires are not twisted.
11. Screw in the swivel pin.
12. Test the center of balance by lifting weight stand by the swivel. The bridle wires should be taut and the bushing on the plate hanging centered below the swivel.
13. Seize the swivel pin by looping a wire through the hole on the flatten head of the pin and the interior hole of the swivel. Tighten by twisting the wire. If you are going to attach the bridle directly to the strain cable delay seizing wire until then.
14. Place the weight stand on the plate side with the legs pointing up.
15. Fair the electrical leads connected to the Neoprene male connector mated to the stainless bulkhead adapter through the Swagelock coupling nut so the wires protrude out the threaded end.
16. Mate the bulkhead adapter to the Swagelock coupling nut.
17. Fair the electrical wires through the Swagelock male run "T" with the thermistor capsule for T-WATER fed out the horizontal opening of the "T", and the remaining wires out the end opposite the coupling nut.
18. Without twisting the wires tighten the upper locking nut against the Swagelock male run "T".
19. Feed the electrical wires through the bushing on the plate so the wires extend out the short side of the bushing.
20. Without twisting the wires tighten Swagelock male run "T" against bushing. At this stage all wires are through the plate except the T-WATER capsule, which is faired through the horizontal opening of the Swagelock male run "T" and a Swagelock coupling nut, but is not yet secured.
21. Turn weight stand so it is free-standing on its legs with the plate up.
22. Fair electrical wires through long stainless nipple.
23. Without twisting wires tighten nipple against bushing.
24. Fair electrical wires through stainless coupling.
25. Without twisting wires tighten coupling against nipple.

26. If the electrical connector is not attached to the electrical wires, do so at this stage.
27. Fair the electrical wires from the thermistor probe through the locking nut of the Swagelock male connector. Insure that the little or back ferrule cone is nearest the pointed end of the probe. The cones of the ferrules should taper towards the blunt end or the end of the probe with the wires attached.
28. Fair the electrical wires from the probe through the fitting body of the Swagelock male connector.
29. Attach electrical connector to wires from the thermistor probe which can mate with connector mentioned in step (26). Usually the thermistor probe already comes with steps (27)-(29) completed, that is, with the Swagelock fitting and the proper electrical connector attached to the probe. These steps are given in case any repairs are needed at the blunt end of the probe.
30. Mate the electrical connectors and stuff excess wire into stainless nipple.
31. Insert thermistor probe plus Swagelock male connector into coupling. At this stage the Swagelock fittings are free to move on the probe.
32. IMPORTANT Without turning the probe, make-up the Swagelock fittings. First seat fitting body against the stainless coupling. Then holding weight stand and fitting body rigid, make-up coupling nut. Now the probe should be connected to the weight stand.
33. Inspect all joints to see if secure. Do not twist probe!!
34. Invert assembly so that the pointed tip of the probe is pointed down and swivel end is up.
35. Fill interior of the assembly with silicone or similar oil through the horizontal opening in the Swagelock male run "T". Use of a syringe is recommended to control filling rate and to reduce air blocks. Continue filling until oil drips out fitting. Then turn assembly on its side with the open part of the "T" up. Continue filling until oil runs out opening.
36. Stuff excess wires connecting thermistor capsule back into Swagelock male run "T".
38. Seat capsule into "T" wiping off excess oil.
39. Tighten Swagelock nut onto "T" with thermistor end of the capsule protruding. Unit is now ready to be connected to strain cable and electrical cable.

To change probes simply reverse steps (38)-(30) if there is no internal damage to wiring between the electrical connectors. Remember in any case the filling oil should be drained before any joints are loosened.

VI OPERATIONAL PROCEDURES

I. PRE-FIELD TESTS

To insure successful operations in the field several tests should be done before leaving the dock. Before loading the boat assemble the units except there is no need to attach the strain cable to the weight stand. However, attach electrical cable to the weight stand connector, and connect the other end of the electrical cable to the monitor box and the Valhalla read-out to monitor box.

A. BATTERY CHECK-LOW POWER With the power supply switch in LO (far right position), and Valhalla read-out buttons: DC/V, 2, and POWER, depressed; push down on the READ PWR SUP spring loaded button. The voltage on the Valhalla should be approximately .4000 volts DC. If the value is significantly different from .4000 volts DC, adjust with the LO VOLTAGE ADJUST 10 turn potentiometer. This may be accomplished by moving the black locking lever on the outer portion of the dial to the left (unlock), then turning the large black knob until the voltage reads .4000 volts DC with the READ PWR SUP button depressed. Upon adjustment move locking lever to the right (lock). If the voltage is unstable or can not be trimmed to the proper value: (1) check to see if the proper buttons and switch positions are used; if this does not fix the situation (2) open the monitor box by removing the four screws around the rim of the face plate, take off plate and replace the Lo power mercury D cell.

BATTERY CHECK-HIGH POWER With the power supply switch in HI (far left position), and Valhalla read-out buttons: DC/V, 20, and POWER, depressed; push down on the READ PWR SUP spring loaded button. The voltage on the Valhalla should be approximately 12 volts. No adjustment can be made. If the value is significantly different than 12 ± 1 volts open monitor case as described above and change batteries.

B. ELECTRICAL CONTINUITY CHECK With the unit assembled and the POWER SUPPLY switch to off (center position) and the Valhalla read-out buttons: DC/V, 200, and POWER buttons depressed, the value on the Valhalla should be 0.000 for each position of the THERMISTOR switch except RES.. Any non-zero value indicates possible corrosive electrolytic effects or thermocouple effects (if HI power has been turned on recently). If the value does not decay to zero after 15 minutes that particular thermistor is defective and can not be used except if the non-zero value is small and the off-set is noted before and after each reading in the field. If all thermistors show a non-zero off-set change probes.

C. CABLE CHECK With the unit assembled and the POWER SUPPLY switch to off, and the Valhalla read-out buttons, k, 200, and POWER, depressed, and the THERMISTOR switch to RES.; the value on the Valhalla should be approximately 3 ohms stable for the short cable and approximately 6 ohms stable for the long cable. If the reading is not stable change cables. Also check for shorts, cuts, etc. on defective cable and check connector plugs for poor contact, corrosion, broken pins. Often poor connections can be fixed by cleaning connector pins with a water repellant solvent such as WD-40 and regreasing with silicone grease.

D. THERMISTOR CHECK With the unit assembled, DIFF BRIDGE/ DIRECT switch to DIRECT, POWER SUPPLY switch to LO, and Valhalla read-out buttons: DC/V, 200, and POWER, depressed; turn THERMISTOR switch to each position while placing finger over the appropriate thermistor on the probe. The voltage reading on the Valhalla should go down rapidly as it heats up due to your body heat. If the value goes up either the thermistor is bad or the operator is very ill. If the former disregard the value of that thermistor. If the value of T 2 REF goes up during this check - CHANGE PROBES!! as that is the reference thermistor for differential gradient measurements. In dire situations a defective reference thermistor can be circumvented by taking all the operative thermistor readings in the DIRECT mode.

E. MECHANICAL CHECKS

1. OIL LEAKS Inspect all joints for signs of oil leaks. If oil is present make certain joint is tight. If oil is found on the probe body or near the thermistor, this suggests a failure in the fiberglass rod or the epoxy collars around the thermistors. CHANGE PROBES!! In dire situations pin-hole leaks may be temporarily repaired by applying RTV then covering with electrical tape. Immediately redo the ELECTRICAL CONTINUITY CHECK described above. If the leaks are flowing or the probe is visibly broken CHANGE PROBES!! as on the next lowering the probe may actually break off and cause flooding of the electrical connectors. A slightly bend probe can be straightened as long as the fiberglass interior rod is not fractured.

2. BRIDLE CHECK Inspect bridle for frayed wires. If the individual wires are broken replace that member. Temporary repairs can be made by taping at the fray but replace as soon as possible. The main danger here from frayed or cut strands is cuts to the operators while handling. Make sure bolts securing eyebolts to weight stand are tight. Inspect swivel connection between the bridle and the strain cable MAKE SURE swivel pin is seized with wire, otherwise pin may unseat and place the entire strain of the probe and the weight stand on the electrical cable.

3. WEIGHTS CHECK Insure that the weights are secured to the base of the weight stand.

4. STRAIN CABLE CHECK If spooling the strain cable onto the winch drum for the first time insure that the end of the cable is stapled or otherwise fastened securely to the drum. DO NOT rely on the friction of the upper wraps of the cable to secure the cable to the drum and prevent run away of the cable. If the cable is already spooled on the drum, unspool the cable to the fastened end to check for frayed wires, kinks, and to insure that the end is attached firmly to the drum. If the cable is badly frayed change strain cables. Temporary repairs can be made by taping breaks if only a few wires are frayed or broken; but this is a dangerous procedure risking the loss of the probe and weight stand and/or damage to the electrical cable.

5. WINCH CHECK While still at the dock check to see if the winch is operating properly, that is the drum is free rolling with the brake off, and the brake can be operated easily.

2. FROM DOCK TO STATION, OR FROM STATION TO STATION

Transport unit to station with probe/weight stand tightly secured so that they do not slam with the movement of the boat. The Valhalla and the Monitor should be disconnected and stored in their waterproof Xero boxes in a secure dry place. NEVER TRANSPORT PROBE UNIT WITH THE VALHALLA AND THE MONITOR CONNECTED!!! The on-deck connector of the electrical cable which mates to the monitor panel should be protected from spray. All spare strain cable should be spooled on the drum of the winch and the winch locked during transport. The electrical cable should be stored on its separate drum and secured. It is not necessary to disconnect the electrical cable from the connector on the weight stand if the connector join is wrapped with electrical tape and both the weight stand and the electrical cable drum are secured against movement during transport. The drum for the electrical cable should be stored such that it can not be stepped on or otherwise damaged by loose debris breaking loose during transit.

3. ON STATION

A. PRE-LOWERING - ANCHORING Before any attempts at measurements using the probe unit are made, the BOAT MUST BE SECURELY ANCHORED with a minimum of two anchors. This is to prevent any possibility of using the probe as an anchoring point on the bottom. The probe on the bottom can act as a drilled-in anchor potentially causing structural damage to the probe and losing both water-tight integrity and electrical continuity of the unit.

B. PRE-LOWERING CHECK Once the boat is anchored securely insure that the swivel pin is seized to the swivel on the strain cable and all the underwater connectors are snugged tight and taped with plastic electrical tape. Make sure that the electrical cable is slack-mounted to the strain cable just above the swivel so that when the strain cable is taut there is no tension on the electrical cable. This should be tested by grasping the strain cable above the swivel and pulling until the bridle cables are taut. If the electrical cable is properly slack mounted it can be moved freely with the bridle and strain cable taut. After several lowerings the attachment point may be changed as the electrical cable tends to twist around the strain cable as the weight stand and the probe rotate about the swivel.

C. LOWERING The weight stand and probe are placed in the vertical position with the probe side down. The unit is lowered so the probe is in the water and the top of the weight stand is awash. At this time make a final inspection of the attachment areas - the swivel, bridle, and electrical plugs. Particularly make sure (1) the bridle cables are free and not looped about the eyebolts; (2) the weight stand and probe unit are vertical with the probe pointing down; and (3) the electrical cable is not attached to the monitoring box. Now lowering actually may begin. As the strain cable is payed out the electrical cable also is released from its separate drum to insure slack in the electrical cable. Lowering speeds are variable and are functions of the weather and sea conditions. Ideally the winch should free-wheel to allow maximum penetration with the given momentum of the weight stand/probe unit. However, the lowering speed should be the fastest consistent with preventing (1) casting loops on the winch drum or (2) putting strain on the electrical cable. In shallow depths of lakes entry into the bottom will be seen as a sudden slackening of the strain cable or in deeper water as a sinusoidal vibration of the strain cable which is the translation of the impact on the bottom up the wire.

D. ON BOTTOM Upon entry the winch should be stopped but permit sufficient cable excess so that both the strain cable and the electrical cable are slack. CAUTION!! Do not pay out too much excess as this may cast loops on the bottom about the weight stand and make pull-out difficult. The cable is sufficiently slack if one can surge the cable back and forth simply by grasping the cable above the water line but below the first pulley block on the boat. The winch drum should be left UNLOCKED and the slackness of the cable tested periodically to prevent the probe from becoming an anchor for the boat. Anchoring by the probe not only may cause structural damage to the cable and probe but also the surging of the boat against the inadvertent anchor of the probe imparts vibrational mechanical energy to the probe which causes errors and drift in the heat flow measurements.

Once the probe is in the bottom the on-deck read-outs may be attached to the electrical cable. First the electrical cable to the Monitor box via the key way connector. Then the Valhalla read-out to the Monitor box by banana plugs. Make sure the live side is connected to each at the red terminals and the ground side is connected to the black terminal on the Monitor and the blue terminal on the Valhalla marked common.

**FIGURE 8
Data Sheet**

STATION _____ POSITION _____ DROP TIME _____
 DATE _____ ON BOTTOM _____
 DEPTH _____ METHOD _____ START MEAS. _____
 OPERATOR _____ ON DECK _____

LOW POWER !!! WAIT 10-15 minutes!!!

HIGH POWER

(ALWAYS IN DIRECT MODE)

MODE SWITCH VOLTAGE COMMENTS
 POSITION

SWITCH VOLTAGE TIME COMMENTS
 POSITION

D BAT TRIM TO _____

BAT READ _____

D T-2 _____

T-2 _____

B T-1 _____

T-1 _____

B T-3 _____

T-3 _____

B T-4 _____

T-4 _____

B T-5 _____

T-5 _____

B T-W _____

T-W _____

D RES _____

D BAT TRIM TO _____

BAT READ _____

D T-2 _____

T-2 _____

B T-1 _____

T-1 _____

B T-3 _____

T-3 _____

B T-4 _____

T-4 _____

B T-5 _____

T-5 _____

B T-W _____

T-W _____

D BAT TRIM TO _____

BAT READ _____

D T-2 _____

T-2 _____

D T-1 _____

T-1 _____

D T-3 _____

T-3 _____

D T-4 _____

T-4 _____

D T-5 _____

T-5 _____

D T-W _____

T-W _____

D BAT _____

BAT _____

At this time the depth of penetration of the probe may be checked before the beginning of official readings by interrogation of the thermistors. With the Valhalla buttons: DC/V, 2, and POWER, depressed; and the Monitor switches DIFF BRIDGE/DIRECT to DIRECT, POWER SUPPLY to LO, the THERMISTOR switch is rotated sequentially from T 2 clockwise to T Water. Depending on which probe is used and with experience in a given area, the preliminary values read on the Valhalla should indicate similar temperature values for all thermistors except T WATER. Remember the temperature values should be similar this does not mean the actual voltage values read out on the Valhalla should necessarily be similar. For example if thermistors T 1 through T 4 all give similar temperature values and T 5 and T WATER are similar; then the probe has penetrated only through T 4 whereas T 5 and T WATER are in the water column. These are check readings only and should not be entered on the data sheet as the thermistors after entry are undergoing dissipation of the thermal energy imparted by penetration and thus are not at stable readings. A possible way to indicate the end of the dissipation of the entry is to wait until the readings of the bottom thermistor T 1 become stable. In any case NO RECORDED READINGS SHOULD BE MADE UNTIL 20 TO 30 MINUTES AFTER ENTRY. This time may be used to obtain the position of the station and prepare the data sheets for actual usable readings.

E. MEASUREMENTS

1. TEMPERATURE GRADIENT At the end of the thermal entry shock period actual measurements may begin. The procedures are specified on the data sheet and measurements should begin on the left side. For ALL measurements for the left side of the data sheet the POWER SUPPLY switch should be on LO or the far right position. The battery check is the first step as described in section I-A of the Operational Procedures. With the Valhalla buttons: DC/V, 2, and POWER, depressed; and the DIFF BRIDGE/DIRECT switch to DIRECT (this step is indicated on the data sheet by a D (DIRECT) in the mode column); press down on the READ PWR SUP button. The reading on the Valhalla should be approximately .4000 volts. One may trim the voltage to exactly .4000 volts by using the LO VOLTAGE ADJUST as described in section I-A. However variations in the last decimal place are acceptable as long as the actual value is recorded in the space on the data sheet next to "BAT TRIM TO". If the battery reading is acceptable thermistor readings may begin. Turn the THERMISTOR switch to T 2, and note its value from the Valhalla on the sheet. This value is a direct reading of the voltage of the reference thermistor and is critical to the following differential readings. If for any reason the reading of T 2 is not stable take the remaining readings of the thermistors in the DIRECT mode and ignore the instructions to switch to the B or DIFF BRIDGE mode. This will cause a loss of precision, but will salvage the station. If the value of T 2 is stable and recorded now put the DIFF BRIDGE/DIRECT switch up to DIFF BRIDGE. This instruction is indicated on the data sheet by a B (BRIDGE) in the mode column. ~~Depending on the probe used~~ To gain maximum precision either the 200 mv or 2 button on the Valhalla should be depressed for differential readings. The value is actually the difference between the reference thermistor and the reading thermistor so that the sign of the voltage is critical and should be carefully recorded along with the numerical value on the data sheet. Following the instructions on the data sheet thermistors T 1, T 3, T 4, T 5, and T WATER should be interrogated and the values recorded. The position RES on the

THERMISTOR switch should be read in the DIRECT mode. The reading of RES is an indication of the resistance of the cable system so the buttons on the Valhalla k Ω , 200 mv, and POWER should be depressed. Wide variations in this value indicate possible shorts or leaks in the electrical system. The RES measurement need only be made at the end of the first and last cycle of measurements. After reading RES do not forget to depress the DC/V buttons on the Valhalla. Three cycles of gradient measurements are given on the left side of the data sheet. Three sets of measurements are needed to insure the system has come to thermal equilibrium particularly as the time of the dissipation is so variable.

2. THERMAL CONDUCTIVITY As noted on the data sheet all measurements recorded on the right side are in the DIRECT mode. Also as these readings are taken using all the batteries in the Monitor, the voltage values are higher so the 20 button on the Valhalla should be depressed. The actual time of these measurements must be noted with respect to the time that the POWER SUPPLY switch is moved to the far left or HI position. It is extremely important that the start time and either the actual or elapsed time from the switch to HI are noted. As explained in the theoretical section, this measurement is valid for thermal conductivity determinations only if the time history of the self-heating of each thermistor is known. If inadvertently the switch is moved to HI or the time record is stopped or discontinued, turn the POWER SUPPLY switch to OFF (center position) and wait at least 10 minutes before trying again. To avoid errors in reading or time marking, two people should take the thermal conductivity measurements: (1) recording the time and the values on the Valhalla (2) calling out the readings at the command of the recorder and operating the Monitor switches. The self-heating of the thermistors during HI power operations does locally change the thermal regime of the sediments; accordingly thermal conductivity measurements should only be taken after satisfactory thermal gradient measurements.

F. RETRIEVAL OF PROBE Upon completion of the measurements and recording them on the data sheet for that station. The probe can be recovered following the reverse of the lowering procedure. First, disconnect the Valhalla and the Monitor from the electrical cable and store them in a secure, dry place. Protect the free end of the electrical cable from spray. Now take up the strain on the strain cable while insuring that the electrical cable is still slack. Before taking up the strain cable on the winch insure that the strain cable is vertical. This operation is critical as any non-vertical lift while the probe is still in the bottom may damage the probe. Wind-up the cable on the winch slowly until pull-out which will be indicated by an easing of the effort to operate the winch. As the strain cable is taken up also retrieve the electrical cable and store the recovered electrical cable on its own drum. As the electrical cable is left slack it may wrap about the strain cable. If this happens recover as much as possible and raise until the strain relief attachment point is reached just above the swivel. UNDER NO CIRCUMSTANCES WIND THE ELECTRICAL CABLE ON THE SAME DRUM AS THE STRAIN CABLE!!! If necessary fake the twisted wires on on the deck of the boat until they can be separated at the strain relief attachment. Many of the twisting problems can be solved by experience in determining the optimum amount of wire out for a given depth and by keeping an adequate but not excessive amount of slack in the electrical cable. In the worse case and as a last resort, detach the electrical cable at the weight stand connector and separate the two

cables. In general it is much better NEVER to disconnect the underwater connectors once away from the dock. If such disconnections are required make sure the active parts of the connectors are protected from moisture by placing dummy mates on them or other protective measures.

With both wires untwisted, lift the probe and weight stand from the vertical to horizontal position and place on its riding cradle on the boat. Wipe clean and check for damage after securing to the cradle. In particular look for misalignment of the probe, damage to the exposed thermistors, loose joints, and oil leaks. After the on-deck read-outs, data books, the probe, and cables, etc. are safely and securely stored then raise the anchor. Do not try to save time by storing gear underway!!

4. STORAGE-MAINTENANCE

At the end of the sampling day back at dock side, all exposed parts, that is, the weight stand and probe, and exposed electrical cable should be cleaned and flushed thoroughly with fresh water. It is desirable to take the weight stand/probe assembly back to your quarters at night to avoid vandalism on the boat, etc. and to check for leaks and damage under better lighting conditions than at dockside. When transporting the probe, it should be protected by shielding in a plastic core liner to avoid damage to the exposed thermistors. It is not necessary to disassemble the weights every night, but is a good practice to loosen and then retighten the locking nuts daily to avoid corrosive freeze-ups. If operations are to be suspended for longer than four days disassemble the weights and clean and bath the nuts, bolts, and washers in light machine oil. Do not reassemble the weights to the weight stand until new operations start.

REMEMBER THE TOTAL UNIT IS AN EXPENSIVE SCIENTIFIC INSTRUMENT AND ALTHOUGH RUGGED IT MUST BE TREATED WITH CARE TO INSURE PRECISE AND RELIABLE OPERATION.

If storage is for longer than one month, remove all batteries from both the Monitor and the Valhalla. The on-deck units should be treated as delicate laboratory instruments and stored properly, that is not in a garage or any area which is damp or undergoes wide range of temperature fluctuations. It is advisable to store all the parts in a clean, dry, temperature controlled area. The electrical cable should be stored coiled on a drum in a position where the cable can not unravel or be crushed. The probe and weight stand unit need not be disassembled if properly washed and cleaned. For long storage coat with a light machine oil all non stainless fittings. The probe/weight stand unit should be stored upright with probe tip up and vertical. NEVER LEAN THE PROBE AGAINST ANYTHING BUT ALWAYS STORE FREE STANDING ON THE LEGS OF THE WEIGHT STAND. Spare probes not oil filled may be stored horizontally in their protective liners. But store the liners so they do not roll.

For reactivation, redo PRE-FIELD TESTS as described at the beginning of the OPERATIONAL PROCEDURES section.

VII. DATA REDUCTION

Four programs are listed, each having an introductory section describing purpose, basic operation, and data input procedure. All programs are written in FORTRAN IV using an IBM 026 keypunch, and were run on Control Data Corporation 6400 and 7600 series computers.

Program ANNUAL computes the theoretical temperatures and heat flow values expected over the period of one year, assuming a sinusoidal bottom temperature variation. Program CURVE uses the individual thermistor calibration data to give a continuous curve of temperature as a function of resistance. Program TABLE uses CURVE results to print a table for direct conversion of voltage to temperature for field use. Program HEAT, which also uses CURVE results, analyzes low power data to give temperatures, thermal gradients, and heat flow values. Thermal conductivity values can either be assumed constant, or read in as data. The high power data reduction section of HEAT cannot be completed before satisfactory thermal conductivity calibration is finished, and is not included in this report.

In addition to a listing of each program, a sample page of output from each program is included for reference. A sample data sheet from the field, the corresponding data cards, and the resulting output are included for program HEAT.

Thermistor calibration parameters for the 22 thermistors in the four rods and two weight stands are given in Appendix "B". The values for the fixed resistors in the two Monitor boxes are given in Appendix "C". The appropriate values from these appendices must be inserted in the programs according to the probe rod and Monitor box being used.

Program Listing

1. PROGRAM ANNUAL (INPUT, OUTPUT)

27

ANNUAL (Cont)

```

30.    D1=TEMP(J)-TEMP(J+1)
31.    G1=5000.*D1
32.    H1=D1*C*50000.
33.    PRINT 44,D1,G1,H1
34.    44 FORMAT (50X,F10.3,7X,F10.1,7X,F10.2)
35.    50 CONTINUE
36.    J=5
37.    PRINT 40,J,X(J),TEMP(J)
38.    J=16
39.    X(16)=0.
40.    TEMP(J)=A+B*COS(P)
41.    107 PRINT 108,X(J),TEMP(J)
42.    108 FORMAT (/,9X,*WATER*,6X,F10.3, 4X,F10.3,////)
43.    150 CONTINUE
44.    200 CONTINUE
45.    STOP
46.    END

```

Sample Output

KONO LAKE TEMPERATURE VARIATION MODEL AT SURFACE DEPTH = 0 METERS

TMAX =25.000 DURING MONTH 0. TMIN = 0 DURING MONTH 6.0 CONDUCTIVITY = .00180 DIFFUSIVITY = .00210

MONTH NUMBER 0

THERMISTOR	DEPTH (CM)	TEMPERATURE	DELTA T	GRADIENT/KM	HEAT FLOW UNITS
1	138.000	15.311			
2	118.000	16.315	-1.004	-5019.5	-90.35
3	98.000	17.471	-1.156	-5780.8	-104.05
4	78.000	18.777	-1.306	-6531.9	-117.58
5	58.000	20.225	-1.447	-7236.9	-130.26
WATER	0	25.000			

MONTH NUMBER .50

THERMISTOR	DEPTH (CM)	TEMPERATURE	DELTA T	GRADIENT/KM	HEAT FLOW UNITS
1	138.000	16.233			
2	118.000	17.227	-.994	-4971.4	-89.48
3	98.000	18.331	-1.104	-5518.9	-99.34
4	78.000	19.531	-1.200	-5999.8	-108.00
5	58.000	20.805	-1.274	-6372.1	-114.70
WATER	0	24.574			

MONTH NUMBER 1.00

THERMISTOR	DEPTH (CM)	TEMPERATURE	DELTA T	GRADIENT/KM	HEAT FLOW UNITS
1	138.000	16.900			
2	118.000	17.817	-.917	-4584.4	-82.52
3	98.000	18.794	-.976	-4880.9	-87.86
4	78.000	19.805	-1.012	-5058.9	-91.06
5	58.000	20.820	-1.015	-5073.1	-91.32
WATER	0	23.325			

CURVE

Program Listing

```

**PROGRAM CURVE(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)**

1. PROGRAM CURVE(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C LANGUAGE - FORTRAN IV KEYPUNCH - IBM 026
C
C THIS PROGRAM WAS MODIFIED FROM A DECK SUPPLIED BY T.C. LEE OF
C U.C. RIVERSIDE. IT TAKES RESISTANCE VS. TEMPERATURE CALIBRATION DATA
C FOR A THERMISTOR AND GIVES A LEAST - SQUARED CURVE MATCH TO THE DATA
C USING A CONTINUOUS FUNCTION FOR TEMPERATURE (KELVIN)
C  $T(R) = 1/(\alpha + \beta \cdot \ln(R) + \gamma \cdot \ln(R)^3)$ 
C TO CONVERT TO CELSIUS C, 273.16 IS SUBTRACTED.
C THE INITIAL DATA INPUT CONSISTS OF ONE CARD GIVING THE NUMBER N
C OF R VS T DATA POINTS, FOLLOWED BY RMAX, THE MAXIMUM RESISTANCE, AND
C RINT, THE RESISTANCE INTERVAL, IN THE TABLE OF R VS T PRINTED USING
C THE FUNCTION DEFINED ABOVE. (SEE READ STATEMENT 5) THESE
C PARAMETERS ARE ASSUMED TO BE THE SAME FOR ALL THERMISTORS.
C DO LOOP 200, INDEX L, GOVERNS THE NUMBER OF THERMISTORS TO BE
C CALIBRATED.
C FOLLOWING THE INITIAL CARD ARE CARDS CONTAINING THE N VALUES
C OF TEMPERATURE IN 8010.0 FORMAT, FOLLOWED BY THE CORRESPONDING N
C VALUES OF RESISTANCE, IN THE SAME ORDER. (SEE READ STATEMENT 13)
C THE PRINTOUT GIVES THE BEST FIT FOR THE 3 PARAMETERS ALPHA, BETA,
C AND GAMMA, FOLLOWED BY THE N VALUES OF OBSERVED TEMPERATURE,
C OBSERVED RESISTANCE, CALCULATED RESISTANCE, AND THE DIFFERENCE
C BETWEEN THESE 2 VALUES OF RESISTANCE. FINALLY, THE TABLE OF
C RESISTANCE VS TEMPERATURE IS PRINTED.
C NOTE THAT DOUBLE PRECISION IS USED FOR MANY VARIABLES IN THE
C PROGRAM, INCLUDING ALL REAL VARIABLE DATA INPUT. ALSO NOTE THE USE
C OF SPECIFIC TAPES FOR READ AND WRITE STATEMENTS IN SOME INSTANCES.

2. DOUBLE PRECISION RT,T,X,Y,ALPHA,BETA,GAMMA,RLOG,RC,RINT,RMAX,CF
3. DIMENSION TITLE(18),T(20),RT(20),X(20),Y(20),TCAL(20),RTAT(50,8),
+TAT(30,8),DIFF(20),CF(6)
C N IS NUMBER OF DATA POINTS, RMAX IS MAX RESISTANCE TO BE TABULATED
C RINT IS INTERVAL BETWEEN RESISTANCES IN TABLE.
4. READ 5,1,RMAX,RINT
5. 5 FORMAT (I2,DF,0,08.0)
6. PRINT 7,1,RMAX,RINT
7. 7 FORMAT(1//,9X,*,NUMBER OF DATA POINTS = *,I2,5X,*,MAXIMUM RESISTANCE
+ TABULATED = *,F8.1,5X,*,RESISTANCE INTERVAL = *,F8.2,/)
C DO LOOP, INDEX L, GOVERNS THE NUMBER OF THERMISTORS TO BE
C CALIBRATED
8. DO 200 L=1,6
9. RC=RMAX
C READ 72 CHARACTER TITLE FOR EACH THERMISTOR
10. READ(5,10)(TITLE(K),K=1,18)
11. 10 FORMAT (18A4)
12. WRITE(6,11)(TITLE(K),K=1,18)
13. 11 FORMAT (1H1,//////18A4///)
C READ N VALUES OF TEMPERATURE IN SEQUENCE
14. READ 13,(T(I),I=1,N)
C READ N VALUES OF CORRESPONDING RESISTANCE IN SEQUENCE
15. READ 13, (RT(I),I=1,N)
16. 13 FORMAT (8D10.0)
17. CF(1)=5.1
CAUTION - IS DOUBLE = REAL EXPRESSION CORRECT *****
18. CF(2)=3.9
CAUTION - IS DOUBLE = REAL EXPRESSION CORRECT *****
19. CF(3)=3.
CAUTION - IS DOUBLE = REAL EXPRESSION CORRECT *****
20. CF(4)=2.1
CAUTION - IS DOUBLE = REAL EXPRESSION CORRECT *****
21. CF(5)=1.6
CAUTION - IS DOUBLE = REAL EXPRESSION CORRECT *****
22. CF(6)=1.2
CAUTION - IS DOUBLE = REAL EXPRESSION CORRECT *****

```

Note - Caution messages result from use of double precision variables and do not indicate an error.

CURVE (Cont)

```

23. 07 15 J1=1,6
24. 03 15 J2=1,3
25. I=J2+3*(J1-1)
25. RT(I)=RT(I)-CF(J1)
27. 15 CONTINUE
28. 03 19 I=1,N
29. XI(I)=DLX(RT(I))
30. 19 Y(I)=1.000/(T(I)+273.1600)
31. CALL LEAST2 (N,X,Y,ALPHA,BETA,GAMMA)
32. PRINT 22, ALPHA, BETA, GAMMA
33. 22 FORMAT (5X,*ALPHA = *,D20.13,5X,*BETA = *,D20.13,5X,*GAMMA = *,
+D20.13,/)
34. PRINT 30
35. 30 FORMAT (20X,*OHMS*,16X,*T OBS*,18X,*T CALC*,14X,*DIFF*)
36. 03 39 K=1,N
37. TCAL(K)=1.000/(ALPHA+BETA*X(K)+GAMMA*X(K)**3)-273.1600
38. DIFF(K)=TCAL(K)-T(K)
39. PRINT 31, RT(K), T(K), TCAL(K), DIFF(K)
40. 31 FORMAT (7,15X,F12.5,7X,F12.5,8X,F15.5,5X,F15.5)
41. 39 CONTINUE
42. 40 03 49 J = 1,8
43. 03 49 I=1,50
44. RLOG=DLG(RC)
45. TMAT(I,J)=1.000/(ALPHA+BETA*RLOG+GAMMA*RLOG**3)-273.1600
46. RTMAT(I,J) = RC
47. 49 RC=RC-FINT
48. WRITE( 6,51)
49. 51 FORMAT (1H1,/)
50. WRITE( 6,52)
51. 52 FORMAT (315H OHMS T CENT),/)
52. 03 59 I=1,50
53. WRITE ( 6,53)
1 RTMAT(I,1),TMAT(I,1),RTMAT(I,2),TMAT(I,2),RTMAT(I,3),TM
1AT(I,3),RTMAT(I,4),TMAT(I,4),RTMAT(I,5),TMAT(I,5),RTMAT(I,6),TMAT
1I,6),RTMAT(I,7),TMAT(I,7),RTMAT(I,8),TMAT(I,8)
54. 53 FORMAT (8(F8.1,F7.3))
55. 59 CONTINUE
56. 107 CONTINUE
57. 203 CONTINUE
58. STOP
59. END

```

C

SUBROUTINE LEAST2(N,X,Y,ALPHA,BETA,GAMMA)

```

1. SUBROUTINE LEAST2(N,X,Y,ALPHA,BETA,GAMMA)
C LEAST SQUARES OF THE FORM Y=ALPHA+BETA*X+GAMMA*X*X*X
C FITTING CURVE X=A+B LN Y **2
2. DOUBLE PRECISION X,Y,C,B,X3,DET,ALPHA,BETA,GAMMA
3. DIMENSION X(1),Y(1),C(3,3),R(3)
4. 03 10 I=1,3
5. R(I)=0.000
6. 03 10 J=1,3
7. 10 C(I,J)=0.000
8. C(1,1)=N
9. 03 10 I=1,N
10. X3 = X(I)**3
11. C(1,2) = C(1,2)+X(I)
12. C(1,3) = C(1,3)+X3
13. C(2,3) = C(2,3)+X(I)*X3
14. C(3,3) = C(3,3)+X3*X3
15. C(2,2)=C(2,2)+X(I)**2
16. B(1) = Y(1)+Y(I)
17. Y(2) = Y(2)+Y(I)*X(I)
18. R(3) = R(3)+Y(I)*X3
19. 30 CONTINUE
20. C(2,1)=C(1,2)
21. C(3,1)=C(1,3)
22. C(3,2)=C(2,3)
23. CALL MTINV(C,3,B,1,DET)
24. ALPHA=B(1)
25. BETA=B(2)
26. GAMMA=B(3)
27. RETURN
28. END

```

C

CURVE (Cont)

```

**SUBROUTINE MATINV(A,N,B,P,DETERM)**
1.  SUBROUTINE MATINV(A,N,B,M,DETERM)
C
C   MATRIX INVERSION WITH ACCOMPANYING SOLUTION OF LINEAR EQUATIONS
C
2.  DOUBLE PRECISION A,P,PIVOT,AMAX,SWAP,T,DETERM
3.  DIMENSION A(3,3),B(3,1),INDEX(50,2),PIVOT(50),IPIVOT(50)
C THE FOLLOWING STATEMENT(S) HAVE BEEN MANUFACTURED BY THE TRANSLATOR TO
C COMPENSATE FOR THE FACT THAT EQUIVALENCE DOES NOT REORDER COMMON---
C DIMENSION IPIVOT(20), A(3,3),B(3,1), INDEX(20,2), PIVOT(20)
C COMMON PIVOT, INDEX, IPIVOT
4.  EQUIVALENCE (IROW,JROW), (ICOLU,JCOLU), (AMAX, T, SWAP)
C
C   INITIALIZATION
C
5.  10 DETERM=1.000
6.  15 DO 20 J=1,N
7.  20 IPIVOT(J)=0
8.  30 DO 550 I=1,N
C
C   SEARCH FOR PIVOT ELEMENT
C
9.  40 AMAX=0.000
10. 45 DO 105 J=1,N
11. 50 IF (IPIVOT(J)-1) 60, 105, 60
12. 60 DO 100 K=1,N
13. 70 IF (IPIVOT(K)-1) 80, 100, 740
14. 80 IF (DABS(AMAX)-DABS(A(I,J,K))) 85, 100, 100
15. 85 IROW=J
16. 90 ICOLU=K
17. 95 AMAX=A(I,J,K)
18. 100 CONTINUE
19. 105 CONTINUE
20. IF (AMAX .EQ. 0.) GO TO 740
21. 110 IPIVOT(ICOLU)=IPIVOT(ICOLU)+1
C
C   INTERCHANGE ROWS TO PUT PIVOT ELEMENT ON DIAGONAL
C
22. 130 IF (IROW-ICOLU) 140, 260, 140
23. 140 DETERM=-DETERM
24. 150 DO 200 L=1,M
25. 160 SWAP=A(IROW,L)
26. 170 A(IROW,L)=A(ICOLU,L)
27. 200 A(ICOLU,L)=SWAP
28. 205 IF (M) 230, 260, 210
29. 210 DO 250 L=1, M
30. 220 SWAP=B(IROW,L)
31. 230 B(IROW,L)=B(ICOLU,L)
32. 250 B(ICOLU,L)=SWAP
33. 260 INDEX(I,1)=IROW
34. 270 INDEX(I,2)=ICOLU
35. 310 PIVOT(I)=A(ICOLU,ICOLU)
36. 320 DETERM=DETERM*PIVOT(I)
C
C   DIVIDE PIVOT ROW BY PIVOT ELEMENT
C
37. 330 A(ICOLU,ICOLU)=1.000
38. 340 DO 350 L=1,M
39. 350 A(ICOLU,L)=A(ICOLU,L)/PIVOT(I)
40. 355 IF (M) 330, 380, 360
41. 360 DO 370 L=1,M
42. 370 B(ICOLU,L)=B(ICOLU,L)/PIVOT(I)
C
C   REDUCE NON-PIVOT ROWS
C
43. 380 DO 550 LI=1,N
44. 390 IF (LI-ICOLU) 400, 550, 400
45. 400 Y=A(LI,ICOLU)
46. 420 A(LI,ICOLU)=0.000
47. 430 DO 450 L=1,N
48. 450 A(LI,L)=A(LI,L)-A(ICOLU,L)*Y
49. 455 IF (M) 550, 550, 460
50. 460 DO 500 L=1,M
51. 500 B(LI,L)=B(LI,L)-B(ICOLU,L)*Y
52. 550 CONTINUE
C

```

MAT10030
 MAT10040
 MAT10050

 MAT10070
 MAT10080

 MAT10110
 MAT10120
 MAT10130
 MAT10140
 MAT10150

 MAT10170
 MAT10180
 MAT10190
 MAT10200
 MAT10210
 MAT10220

 MAT10240
 MAT10250
 MAT10260
 MAT10270

 MAT10290
 MAT10300
 MAT10310
 MAT10320

 MAT10340
 MAT10350
 MAT10360
 MAT10370
 MAT10380
 MAT10390
 MAT10400
 MAT10410
 MAT10420
 MAT10430
 MAT10440
 MAT10450
 MAT10460
 MAT10470
 MAT10480
 MAT10490
 MAT10500
 MAT10510
 MAT10520
 MAT10530
 MAT10540
 MAT10550

 MAT10570
 MAT10580
 MAT10590
 MAT10600
 MAT10610
 MAT10620
 MAT10630
 MAT10640
 MAT10650
 MAT10660
 MAT10670

 MAT10690
 MAT10700
 MAT10710
 MAT10720
 MAT10730
 MAT10740
 MAT10750

CURVE (Cont)

C	INTERCHANGE COLUMNS		
53.	500 70 710 I=1,N		MAT10760
54.	510 L=N+1-I		MAT10770
55.	520 IF (INDEX(L,1)-INDEX(L,2)) 630, 710, 630		MAT10780
56.	630 JROW=INDEX(L,1)		MAT10790
57.	640 JCOLUM=INDEX(L,2)		MAT10800
58.	650 DO 705 K=1,N		MAT10810
59.	660 SWAP=A(K,JROW)		MAT10820
60.	670 A(K,JROW)=A(K,JCOLUM)		MAT10830
61.	705 A(K,JCOLUM)=SWAP		MAT10840
62.	715 CONTINUE		MAT10850
63.	710 CONTINUE		MAT10860
64.	740 RETURN		MAT10870
65.	760 DETERM=J, JDO		MAT10880
66.	RETURN		
67.	END		

Sample Output

WHITE/ORANGE THERMISTOR GROUP 012

ALPHA =	.1330665831348E-02	BETA =	.2407614169990E-03	GAMMA =	.8470312829343E-07
---------	--------------------	--------	--------------------	---------	--------------------

OHMS	T OBS	T CALC	DIFF
7658.10000	5.03900	5.04169	.00269
7652.00000	5.06300	5.05779	-.00521
7651.90000	5.06200	5.05805	-.00395
5595.70000	10.06300	10.06547	.00247
5555.50000	10.06400	10.06617	.00217
5556.60000	10.06100	10.06234	.00134
4747.50000	15.00500	15.00707	.00207
4747.70000	15.00800	15.00758	-.00002
4747.30000	15.00700	15.00979	.00279
3775.00000	20.00700	20.01445	.00745
3775.00000	20.00600	20.01445	.00845
3775.50000	20.00300	20.01043	.00743
3327.40000	25.00000	24.98256	-.01744
3327.00000	25.00400	24.98558	-.01842
3327.10000	25.00300	24.98483	-.01817
2437.40000	30.00300	30.01127	.01127
2437.50000	30.00200	30.01031	.00831
2437.40000	30.00500	30.01127	.00627

CURVE (Cont)

OHMS	T CENT	OHMS	T CENT	OHMS	T CENT	OHMS	T CENT	OHMS	T CENT	OHMS	T CENT	OHMS	T CENT	OHMS	T CENT
8400.0	3.184	7400.0	5.735	6400.0	8.710	5400.0	12.263	4400.0	16.652	3400.0	22.351	2400.0	30.376	1400.0	43.597
8380.0	3.232	7380.0	5.791	6380.0	8.775	5380.0	12.341	4380.0	16.751	3380.0	22.484	2380.0	30.573	1380.0	43.964
8360.0	3.280	7360.0	5.846	6360.0	8.840	5360.0	12.420	4360.0	16.850	3360.0	22.617	2360.0	30.773	1360.0	44.337
8340.0	3.327	7340.0	5.901	6340.0	8.905	5340.0	12.499	4340.0	16.950	3340.0	22.752	2340.0	30.974	1340.0	44.717
8320.0	3.375	7320.0	5.957	6320.0	8.971	5320.0	12.579	4320.0	17.051	3320.0	22.887	2320.0	31.178	1320.0	45.103
8300.0	3.424	7300.0	6.012	6300.0	9.036	5300.0	12.659	4300.0	17.152	3300.0	23.024	2300.0	31.383	1300.0	45.496
8280.0	3.472	7280.0	6.068	6280.0	9.102	5280.0	12.739	4280.0	17.254	3280.0	23.161	2280.0	31.591	1280.0	45.896
8260.0	3.520	7260.0	6.124	6260.0	9.168	5260.0	12.819	4260.0	17.356	3260.0	23.300	2260.0	31.800	1260.0	46.304
8240.0	3.569	7240.0	6.180	6240.0	9.235	5240.0	12.900	4240.0	17.459	3240.0	23.439	2240.0	32.012	1240.0	46.718
8220.0	3.617	7220.0	6.237	6220.0	9.301	5220.0	12.981	4220.0	17.562	3220.0	23.579	2220.0	32.226	1220.0	47.141
8200.0	3.666	7200.0	6.293	6200.0	9.369	5200.0	13.063	4200.0	17.666	3200.0	23.720	2200.0	32.442	1200.0	47.571
8180.0	3.715	7180.0	6.350	6180.0	9.435	5180.0	13.145	4180.0	17.770	3180.0	23.863	2180.0	32.660	1180.0	48.010
8160.0	3.764	7160.0	6.407	6160.0	9.503	5160.0	13.227	4160.0	17.875	3160.0	24.006	2160.0	32.881	1160.0	48.458
8140.0	3.813	7140.0	6.464	6140.0	9.570	5140.0	13.310	4140.0	17.980	3140.0	24.150	2140.0	33.104	1140.0	48.914
8120.0	3.863	7120.0	6.521	6120.0	9.638	5120.0	13.393	4120.0	18.087	3120.0	24.295	2120.0	33.329	1120.0	49.380
8100.0	3.912	7100.0	6.578	6100.0	9.706	5100.0	13.476	4100.0	18.193	3100.0	24.442	2100.0	33.557	1100.0	49.856
8080.0	3.962	7080.0	6.636	6080.0	9.775	5080.0	13.560	4080.0	18.300	3080.0	24.589	2080.0	33.787	1080.0	50.341
8060.0	4.011	7060.0	6.693	6060.0	9.843	5060.0	13.644	4060.0	18.408	3060.0	24.738	2060.0	34.020	1060.0	50.837
8040.0	4.061	7040.0	6.751	6040.0	9.912	5040.0	13.728	4040.0	18.517	3040.0	24.888	2040.0	34.256	1040.0	51.344
8020.0	4.111	7020.0	6.810	6020.0	9.981	5020.0	13.813	4020.0	18.626	3020.0	25.038	2020.0	34.494	1020.0	51.862
8000.0	4.162	7000.0	6.868	6000.0	10.051	5000.0	13.898	4000.0	18.736	3000.0	25.190	2000.0	34.734	1000.0	52.392
7980.0	4.212	6980.0	6.926	5980.0	10.120	4980.0	13.984	3980.0	18.846	2980.0	25.344	1980.0	34.978	980.0	52.934
7960.0	4.262	6960.0	6.985	5960.0	10.190	4960.0	14.070	3960.0	18.957	2960.0	25.498	1960.0	35.224	960.0	53.489
7940.0	4.313	6940.0	7.044	5940.0	10.260	4940.0	14.156	3940.0	19.069	2940.0	25.653	1940.0	35.474	940.0	54.058
7920.0	4.364	6920.0	7.103	5920.0	10.331	4920.0	14.243	3920.0	19.181	2920.0	25.810	1920.0	35.726	920.0	54.641
7900.0	4.415	6900.0	7.162	5900.0	10.401	4900.0	14.330	3900.0	19.294	2900.0	25.968	1900.0	35.981	900.0	55.238
7880.0	4.466	6880.0	7.222	5880.0	10.472	4880.0	14.418	3880.0	19.407	2880.0	26.127	1880.0	36.239	880.0	55.851
7860.0	4.517	6860.0	7.281	5860.0	10.544	4860.0	14.506	3860.0	19.521	2860.0	26.288	1860.0	36.501	860.0	56.481
7840.0	4.568	6840.0	7.341	5840.0	10.615	4840.0	14.594	3840.0	19.636	2840.0	26.449	1840.0	36.766	840.0	57.127
7820.0	4.620	6820.0	7.401	5820.0	10.687	4820.0	14.683	3820.0	19.752	2820.0	26.612	1820.0	37.034	820.0	57.792
7800.0	4.671	6800.0	7.462	5800.0	10.759	4800.0	14.773	3800.0	19.868	2800.0	26.777	1800.0	37.305	800.0	58.475
7780.0	4.723	6780.0	7.522	5780.0	10.831	4780.0	14.862	3780.0	19.985	2780.0	26.942	1780.0	37.580	780.0	59.178
7760.0	4.775	6760.0	7.583	5760.0	10.904	4760.0	14.952	3760.0	20.103	2760.0	27.109	1760.0	37.858	760.0	59.903
7740.0	4.827	6740.0	7.643	5740.0	10.977	4740.0	15.043	3740.0	20.221	2740.0	27.278	1740.0	38.140	740.0	60.650
7720.0	4.879	6720.0	7.705	5720.0	11.050	4720.0	15.134	3720.0	20.340	2720.0	27.448	1720.0	38.426	720.0	61.420
7700.0	4.931	6700.0	7.765	5700.0	11.124	4700.0	15.225	3700.0	20.460	2700.0	27.619	1700.0	38.716	700.0	62.215
7680.0	4.984	6680.0	7.827	5680.0	11.198	4680.0	15.317	3680.0	20.581	2680.0	27.792	1680.0	39.010	680.0	63.038
7660.0	5.037	6660.0	7.889	5660.0	11.272	4660.0	15.409	3660.0	20.702	2660.0	27.966	1660.0	39.307	660.0	63.889
7640.0	5.090	6640.0	7.951	5640.0	11.346	4640.0	15.502	3640.0	20.824	2640.0	28.141	1640.0	39.609	640.0	64.770
7620.0	5.143	6620.0	8.013	5620.0	11.421	4620.0	15.595	3620.0	20.947	2620.0	28.319	1620.0	39.915	620.0	65.684
7600.0	5.196	6600.0	8.075	5600.0	11.496	4600.0	15.689	3600.0	21.070	2600.0	28.497	1600.0	40.225	600.0	66.632
7580.0	5.249	6580.0	8.138	5580.0	11.571	4580.0	15.783	3580.0	21.195	2580.0	28.678	1580.0	40.540	580.0	67.618
7560.0	5.302	6560.0	8.200	5560.0	11.647	4560.0	15.878	3560.0	21.320	2560.0	28.860	1560.0	40.859	560.0	68.644
7540.0	5.356	6540.0	8.263	5540.0	11.723	4540.0	15.973	3540.0	21.446	2540.0	29.043	1540.0	41.183	540.0	69.713
7520.0	5.410	6520.0	8.327	5520.0	11.799	4520.0	16.068	3520.0	21.573	2520.0	29.228	1520.0	41.512	520.0	70.830
7500.0	5.464	6500.0	8.390	5500.0	11.875	4500.0	16.164	3500.0	21.700	2500.0	29.415	1500.0	41.846	500.0	71.997
7480.0	5.518	6480.0	8.454	5480.0	11.952	4480.0	16.261	3480.0	21.829	2480.0	29.604	1480.0	42.186	480.0	73.219
7460.0	5.572	6460.0	8.517	5460.0	12.029	4460.0	16.358	3460.0	21.958	2460.0	29.794	1460.0	42.530	460.0	74.503
7440.0	5.627	6440.0	8.582	5440.0	12.107	4440.0	16.455	3440.0	22.088	2440.0	29.986	1440.0	42.880	440.0	75.852
7420.0	5.681	6420.0	8.646	5420.0	12.185	4420.0	16.553	3420.0	22.219	2420.0	30.180	1420.0	43.235	420.0	77.275

TABLE

Program Listing

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**PROGRAM TABLE(INPUT,OUTPUT)**

1. PROGRAM TABLE(INPUT,OUTPUT)
C
C LANGUAGE - FORTRAN IV KEYPUNCH - IBM 026
C
C THIS PROGRAM PRINTS A TABLE, FOR EACH PROBE THERMISTOR, WHICH
C CONVERTS DIRECT MODE VOLTAGE READINGS ACROSS A THERMISTOR IN
C MILLIVOLTS INTO TEMPERATURE IN DEGREES C. THE LOW POWER VOLTAGE
C OF THE INSTRUMENT PACKAGE MUST BE ADJUSTED TO 400 MILLIVOLTS FOR THE
C TABLES TO BE ACCURATE.
C ALL DATA IS STOPPED WITHIN THE PROGRAM, HENCE NO DATA CARDS ARE
C READ. TO CALIBRATE A NEW SET OF THERMISTORS IN A PROBE, INSERT THE
C COEFFICIENTS A, B, AND G, COMPUTED IN PROGRAM CURVE. (THESE 18 CARDS
C ARE IDENTICAL TO THOSE IN THE PROGRAM HEAT) IF A NEW INSTRUMENT
C PACKAGE IS USED, THE 6 FIXED BRIDGE RESISTANCES F(1) MUST BE
C CHANGED. CABLE RESISTANCE CR MUST BE CHANGED FOR A NEW CABLE. IF
C MORE THAN 30 LESS THAN 6 THERMISTOR TABLES ARE DESIRED, VARY INDEX
C K IN DO LOOP 100.
C THE TABLE IS COMPUTED BY STARTING AT THE HIGHEST VOLTAGE
C DESIRED, VMAX, THEN DECREASING THE VOLTAGE IN INCREMENTS VINT. THE
C NEXT DOUBLE LOOP 49 DOES 40 SUCH DECREASES, AND IS USED TWICE BY
C DO LOOP 70, SO THE MINIMUM VOLTAGE = VMAX-80*VINT.
C
2. DIMENSION F(6),A(6),B(6),G(6),RTNAT(50,8),TPAT(50,8)
C VALUES OF FIXED RESISTORS IN BRIDGE
3. F(1)=4636.1
4. F(2)=4636.2
5. F(3)=4636.3
6. F(4)=4636.6
7. F(5)=4636.7
8. F(6)=4636.8
C ALPHA, BETA, GAMMA ARE COEFFICIENTS FROM T.C. LEES CURVE FITTING
C PROGRAM FOR THERMISTORS
9. A(1)=.1405619148524E-02
10. B(1)=.2366340159203E-03
11. G(1)=.1313227425485E-06
12. A(2)=.1400805645116E-02
13. B(2)=.2375450514980E-03
14. G(2)=.9711314628007E-07
15. A(3)=.1396225545155E-02
16. B(3)=.2332998351121E-03
17. G(3)=.9413025559457E-07
18. A(4)=.1379583760132E-02
19. B(4)=.2+12683442044E-03
20. G(4)=.8102214203783E-07
21. A(5)=.1431790201060E-02
22. B(5)=.2372679173381E-03
23. G(5)=.58+9340173562E-07
24. A(6)=.1371738978022E-02
25. B(6)=.2+21751097243E-03
26. G(6)=.788+964267526E-07
C CR IS THE CABLE RESISTANCE
27. CR=3.
C VINT IS THE VOLTAGE INCREMENT OF THE TABLE
28. VINT=.2
C BL1 IS THE LOW-POWER APPLIED VOLTAGE, NOMINALLY 400 MILLIVOLTS
29. BL1=400.
C VMAX IS THE MAXIMUM VOLTAGE OF THE TABLE
30. VMAX=250.
C DO LOOP 100 INDEX K, GOVERNS NUMBER OF TABLES TO BE COMPUTED
31. DO 100 K=1,6
32. V=VMAX
33. DC 70 L=1,2
34. PRINT 10,K,A(K),B(K),G(K)
35. 10 FORMAT (1H1,*THERMISTOR NUMBER *,I1,10X,*ALPHA =*,E20.13,5X,*BETA
36. +*,E20.13,5X,*GAMMA =*,E20.13,/)
37. 40 DO 45 J = 1,8
38. DO 49 I=1,50
C COMPUTE THERMISTOR RESISTANCE IN DIRECT MODE, SUBTRACT CABLE
C RESISTANCE OF CR OHMS
39. R=F(K)/((BL1/V)-1.1)-CR
C COMPUTE TEMPERATURE FROM PARAMETERS
39. FLOG=ALOG(R)
40. TNAT(I,J)=1./((A(K)+B(K)*FLOG+G(K)*FLOG**3)-273.16
41. *TNAT(I,J)=V
42. 49 V=V-VINT

```

TABLE (Cont)

```

43. PRINT 51
44. 51 FORMAT (IX, 8(15H MV T CENT),/)
45. 07 50 I=1,50
46. PRINT 51,
1 RTMAT(I,1),TMAT(I,1),RTMAT(I,2),TMAT(I,2),RTMAT(I,3),TM
1AT(I,3),RTMAT(I,4),TMAT(I,4),RTMAT(I,5),TMAT(I,5),RTMAT(I,6),TMAT
1(I,6),RTMAT(I,7),TMAT(I,7),RTMAT(I,8),TMAT(I,8)
47. 53 FORMAT(8(F8.2,F7.3))
48. 59 CONTINUE
49. 70 CONTINUE
50. 100 CONTINUE
51. STOP
52. END

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Sample Output

```

- THERMISTOR NUMBER 1      ALPHA = .140561914E524E-02      BETA = .2366340159203E-03      GAMMA = .1013227429485E-06

```

MV		T CENT		MV		T CENT		MV		T CENT		MV		T CENT		MV		T CENT	
250.00	4.873	240.00	7.015	230.00	9.139	220.00	11.258	210.00	13.383	200.00	15.525	190.00	17.695	180.00	19.905	170.00	22.121	160.00	24.346
249.80	4.918	239.80	7.058	229.80	9.182	219.80	11.301	209.80	13.426	199.80	15.568	189.80	17.739	179.80	19.950	169.80	22.162	159.80	24.381
249.60	4.961	239.60	7.101	229.60	9.224	219.60	11.343	209.60	13.469	199.60	15.611	189.60	17.783	179.60	19.994	169.60	22.195	159.60	24.412
249.40	5.004	239.40	7.143	229.40	9.267	219.40	11.386	209.40	13.511	199.40	15.655	189.40	17.826	179.40	20.039	169.40	22.226	159.40	24.443
249.20	5.047	239.20	7.186	229.20	9.309	219.20	11.428	209.20	13.554	199.20	15.698	189.20	17.870	179.20	20.094	169.20	22.257	159.20	24.474
249.00	5.090	239.00	7.223	229.00	9.351	219.00	11.470	209.00	13.597	199.00	15.741	189.00	17.914	179.00	20.128	169.00	22.288	159.00	24.505
248.80	5.133	238.80	7.271	228.80	9.394	218.80	11.513	208.80	13.639	198.80	15.784	188.80	17.958	178.80	20.173	168.80	22.319	158.80	24.536
248.60	5.176	238.60	7.313	228.60	9.436	218.60	11.555	208.60	13.682	198.60	15.827	188.60	18.002	178.60	20.218	168.60	22.350	158.60	24.567
248.40	5.219	238.40	7.356	228.40	9.479	218.40	11.598	208.40	13.725	198.40	15.870	188.40	18.046	178.40	20.263	168.40	22.381	158.40	24.598
248.20	5.262	238.20	7.399	228.20	9.521	218.20	11.640	208.20	13.767	198.20	15.913	188.20	18.090	178.20	20.308	168.20	22.412	158.20	24.629
248.00	5.305	238.00	7.441	228.00	9.563	218.00	11.683	208.00	13.810	198.00	15.957	188.00	18.134	178.00	20.353	168.00	22.443	158.00	24.660
247.80	5.348	237.80	7.484	227.80	9.606	217.80	11.725	207.80	13.853	197.80	16.000	187.80	18.177	177.80	20.398	167.80	22.474	157.80	24.691
247.60	5.391	237.60	7.526	227.60	9.648	217.60	11.767	207.60	13.895	197.60	16.043	187.60	18.221	177.60	20.442	167.60	22.505	157.60	24.722
247.40	5.434	237.40	7.569	227.40	9.690	217.40	11.810	207.40	13.938	197.40	16.086	187.40	18.265	177.40	20.487	167.40	22.536	157.40	24.753
247.20	5.476	237.20	7.611	227.20	9.733	217.20	11.852	207.20	13.981	197.20	16.130	187.20	18.309	177.20	20.532	167.20	22.567	157.20	24.784
247.00	5.519	237.00	7.654	227.00	9.775	217.00	11.895	207.00	14.024	197.00	16.173	187.00	18.353	177.00	20.577	167.00	22.598	157.00	24.815
246.80	5.562	236.80	7.696	226.80	9.818	216.80	11.937	206.80	14.066	196.80	16.216	186.80	18.397	176.80	20.622	166.80	22.629	156.80	24.846
246.60	5.605	236.60	7.739	226.60	9.860	216.60	11.980	206.60	14.109	196.60	16.259	186.60	18.441	176.60	20.667	166.60	22.660	156.60	24.877
246.40	5.648	236.40	7.781	226.40	9.902	216.40	12.022	206.40	14.152	196.40	16.303	186.40	18.485	176.40	20.712	166.40	22.691	156.40	24.908
246.20	5.691	236.20	7.824	226.20	9.945	216.20	12.065	206.20	14.195	196.20	16.346	186.20	18.529	176.20	20.758	166.20	22.722	156.20	24.939
246.00	5.734	236.00	7.866	226.00	9.987	216.00	12.107	206.00	14.238	196.00	16.389	186.00	18.574	176.00	20.803	166.00	22.753	156.00	24.970
245.80	5.777	235.80	7.909	225.80	10.029	215.80	12.150	205.80	14.280	195.80	16.433	185.80	18.618	175.80	20.848	165.80	22.784	155.80	25.001
245.60	5.819	235.60	7.951	225.60	10.072	215.60	12.192	205.60	14.323	195.60	16.476	185.60	18.662	175.60	20.893	165.60	22.815	155.60	25.032
245.40	5.862	235.40	7.994	225.40	10.114	215.40	12.235	205.40	14.366	195.40	16.519	185.40	18.706	175.40	20.938	165.40	22.846	155.40	25.063
245.20	5.905	235.20	8.036	225.20	10.157	215.20	12.277	205.20	14.409	195.20	16.563	185.20	18.750	175.20	20.983	165.20	22.877	155.20	25.094
245.00	5.948	235.00	8.079	225.00	10.199	215.00	12.319	205.00	14.452	195.00	16.606	185.00	18.794	175.00	21.029	165.00	22.908	155.00	25.125
244.80	5.991	234.80	8.121	224.80	10.241	214.80	12.362	204.80	14.494	194.80	16.649	184.80	18.838	174.80	21.074	164.80	22.939	154.80	25.156
244.60	6.033	234.60	8.164	224.60	10.284	214.60	12.404	204.60	14.537	194.60	16.693	184.60	18.883	174.60	21.119	164.60	22.970	154.60	25.187
244.40	6.076	234.40	8.206	224.40	10.326	214.40	12.447	204.40	14.580	194.40	16.736	184.40	18.927	174.40	21.164	164.40	23.001	154.40	25.218
244.20	6.119	234.20	8.249	224.20	10.368	214.20	12.489	204.20	14.623	194.20	16.780	184.20	18.971	174.20	21.210	164.20	23.032	154.20	25.249
244.00	6.162	234.00	8.291	224.00	10.411	214.00	12.532	204.00	14.666	194.00	16.823	184.00	19.015	174.00	21.255	164.00	23.063	154.00	25.280
243.80	6.205	233.80	8.333	223.80	10.453	213.80	12.575	203.80	14.709	193.80	16.867	183.80	19.050	173.80	21.300	163.80	23.094	153.80	25.311
243.60	6.247	233.60	8.376	223.60	10.495	213.60	12.617	203.60	14.752	193.60	16.910	183.60	19.104	173.60	21.346	163.60	23.125	153.60	25.342
243.40	6.290	233.40	8.418	223.40	10.538	213.40	12.660	203.40	14.794	193.40	16.954	183.40	19.148	173.40	21.391	163.40	23.156	153.40	25.373
243.20	6.333	233.20	8.461	223.20	10.580	213.20	12.702	203.20	14.837	193.20	16.997	183.20	19.193	173.20	21.437	163.20	23.187	153.20	25.404
243.00	6.375	233.00	8.503	223.00	10.623	213.00	12.745	203.00	14.880	193.00	17.041	183.00	19.237	173.00	21.482	163.00	23.218	153.00	25.435
242.80	6.418	232.80	8.546	222.80	10.665	212.80	12.787	202.80	14.923	192.80	17.084	182.80	19.281	172.80	21.528	162.80	23.249	152.80	25.466
242.60	6.461	232.60	8.588	222.60	10.707	212.60	12.830	202.60	14.966	192.60	17.128	182.60	19.326	172.60	21.573	162.60	23.280	152.60	25.497
242.40	6.504	232.40	8.631	222.40	10.750	212.40	12.872	202.40	15.009	192.40	17.171	182.40	19.370	172.40	21.619	162.40	23.311	152.40	25.528
242.20	6.546	232.20	8.673	222.20	10.792	212.20	12.915	202.20	15.052	192.20	17.215	182.20	19.415	172.20	21.664	162.20	23.342	152.20	25.559
242.00	6.589	232.00	8.715	222.00	10.835	212.00	12.957	202.00	15.095	192.00	17.258	182.00	19.459	172.00	21.710	162.00	23.373	152.00	25.590
241.80	6.632	231.80	8.758	221.80	10.877	211.80	13.000	201.80	15.138	191.80	17.302	181.80	19.504	171.80	21.755	161.80	23.404	151.80	25.621
241.60	6.674	231.60	8.801	221.60	10.919	211.60	13.043	201.60	15.181	191.60	17.346	181.60	19.548	171.60	21.801	161.60	23.435	151.60	25.652
241.40	6.717	231.40	8.843	221.40	10.962	211.40	13.085	201.40	15.224	191.40	17.389	181.40	19.593	171.40	21.847	161.40	23.466	151.40	25.683
241.20	6.760	231.20	8.885	221.20	11.004	211.20	13.128	201.20	15.267	191.20	17.433	181.20	19.637	171.20	21.892	161.20	23.497	151.20	25.714
241.00	6.802	231.00	8.927	221.00	11.046	211.00	13.170	201.00	15.310	191.00	17.477	181.00	19.682	171.00	21.938	161.00	23.528	151.00	25.745
240.80	6.845	230.80	8.970	220.80	11.089	210.80	13.213	200.80	15.353	190.80	17.520	180.80	19.726	170.80	21.984	160.80	23.559	150.80	25.776
240.60	6.888	230.60	9.012	220.60	11.131	210.60	13.256	200.60	15.396	190.60	17.564	180.60	19.771	170.60	22.030	160.60	23.590	150.60	25.807
240.40	6.930	230.40	9.055	220.40	11.174	210.40	13.298	200.40	15.439	190.40	17.608	180.40	19.816	170.40	22.075	160.40	23.621	150.40	25.838
240.20	6.973	230.20	9.097	220.20	11.216	210.20	13.341	200.20	15.482	190.20	17.651	180.20	19.860	170.20	22.121	160.20	23.652	150.20	25.869

HEAT

Program Listing

PROGRAM HEAT(INPUT,OUTPUT)

```

1.  PROGRAM HEAT(INPUT,OUTPUT)
C
C  LANGUAGE - FORTRAN IV          KEYPUNCH - IBM 026
C
C  THIS PROGRAM IS USED FOR REDUCTION OF DATA TAKEN BY THE CALIF
C  STATE LANDS COMMISSION DURING HEAT FLOW SURVEYS IN CALIF. LAKE
C  BOTTOM SEDIMENTS. EACH HEAT FLOW PROBE HAS A SPECIFIC SET OF THE
C  18 PARAMETERS A(1), B(1), AND G(1) - 3 FOR EACH OF THE 6 PROBE
C  THERMISTORS. THE PROGRAM CURVE IS USED TO GENERATE A, B, AND G FOR
C  THERMISTOR FROM CALIBRATION DATA TAKEN AT VARIOUS TEMPERATURES.
C  IN ADDITION, THE ARRAY F(1) IS USED TO STORE THE PRECISION
C  RESISTORS USED IN THE INSTRUMENT PACKAGE AS PART OF THE WHEATSTONE
C  BRIDGE, AND VARIES FOR EACH PACKAGE.
C  THE INPUT DATA CONSISTS OF 4 CARDS. THE FIRST READS IN CABLE
C  WIRE RESISTANCE IN OHMS, DIRECT MODE CYCLE NUMBER, AND A 68
C  CHARACTER TITLE FOR EACH STATION. (SEE READ STATEMENT 11) THE NEXT
C  3 CARDS CONTAIN THE LOW POWER READINGS FOR THE 3 CYCLES AT EACH
C  STATION. (SEE READ STATEMENT 20) BATTERY VOLTAGES AT BEGINNING AND
C  END OF EACH CYCLE ARE READ IN COLUMNS 1-10 AND 71-80. VOLTAGES FOR
C  THERMISTORS 2,1,3,4,5, AND THE WATER THERMISTOR, RESPECTIVELY, ARE
C  READ IN 10 COLUMN SPACES FROM COLUMN 11 THROUGH 70. ALL VOLTAGES
C  ARE READ IN MILLIVOLTS.
C  A FIFTH CARD FOR CONDUCTIVITY INPUT IS DESCRIBED FURTHER ON.
C  RESISTANCE OF THE REFERENCE THERMISTOR T-2 IS COMPUTED FIRST.
C  FOR BRIDGE MODE READINGS, OTHER RESISTANCES ARE COMPUTED FROM
C  WHEATSTONE BRIDGE EQUATION RELATIVE TO THE RESISTANCE OF T-2. FOR
C  DIRECT MODE READINGS, ALL RESISTANCES ARE COMPUTED DIRECTLY FROM THE
C  MEASURED VOLTAGE DROP ACROSS EACH THERMISTOR.
C  DO LOOP 150 CONVERTS RESISTANCE TO TEMPERATURE FOR EACH
C  THERMISTOR USING THE PARAMETERS A,B, AND G IN THE APPROPRIATE
C  EQUATION. THE TEMPERATURE DIFFERENCE DELTA T AND THE GEOTHERMAL
C  GRADIENT IN DEGREES PER KILOMETER ARE THEN COMPUTED BETWEEN
C  SUCCESSIVE THERMISTORS, EXCLUDING THE WATER THERMISTOR.
C  HEAT FLOW IS ALSO COMPUTED BETWEEN ADJACENT THERMISTORS, USING
C  EITHER ASSUMED VALUES FOR THERMAL CONDUCTIVITY, OR BY READING IN
C  THE MEASURED CONDUCTIVITY VALUES USING A 5F10.0 FORMAT (SEE READ
C  STATEMENT 16) FOR THE LATTER CASE, THE CARD CONTAINING THE 5
C  CONDUCTIVITY VALUES IS INSERTED AFTER THE FIRST CARD CONTAINING THE
C  STATION TITLE, AND BEFORE THE VOLTAGE CARDS. TO USE ASSUMED VALUES
C  OF THERMAL CONDUCTIVITY, REMOVE READ STATEMENT 16 AND INSERT A CARD,
C  DO 18 I=1,5, AND A CARD, C(1)=(DESIRED VALUE), IN PLACE OF THE READ
C  16 STATEMENT.
C  A 20 CM SPACING IS ASSUMED BETWEEN ADJACENT THERMISTORS.
C  LOW POWER DISSIPATION IN MILLIWATTS AND CABLE RESISTANCE IN
C  OHMS ARE PRINTED AT THE END OF THE OUTPUT FOR EACH STATION.
C  PLEASE NOTE THAT THE CLEAR LAKE DATA DECK DOES NOT HAVE THE
C  FIRST DATA CARD DESCRIBED HERE, AND THIS CARD MUST BE ADDED FOR EACH
C  STATION TO USE THE PROGRAM AS WRITTEN WITH THE CLEAR LAKE DATA DECK.
C
2.  DIMENSION TITLE(18),F(6),A(6),B(6),G(6),V(8),R(6),T(6),C(6)
C  VALUES OF FIXED RESISTORS IN BRIDGE
3.  F(1)=4636.1
4.  F(2)=4636.2
5.  F(3)=4636.3
6.  F(4)=4636.6
7.  F(5)=4636.7
8.  F(6)=4636.8
C  A, B, AND G ARE THE PARAMETERS ALPHA, BETA, AND GAMMA TAKEN FROM THE
C  PROGRAM CURVE - THE CURVE FITTING ROUTINE OBTAINED BY CALIBRATION OF
C  EACH THERMISTOR.
9.  A(1)=.1405619148924E-02
10. B(1)=.2366340159203E-03
11. G(1)=.1013227429485E-06
12. A(2)=.1400605645116E-02
13. B(2)=.2375490614880E-03
14. G(2)=.9711314628007E-07
15. A(3)=.1396225549155E-02
16. B(3)=.2382948351121E-03
17. G(3)=.9413025559497E-07
18. A(4)=.1379583760132E-02
19. B(4)=.2412683442644E-03
20. G(4)=.8102214203783E-07
21. A(5)=.1401780201060E-02
22. B(5)=.2372679173381E-03
23. G(5)=.9849340173962E-07
24. A(6)=.1371738978022E-02
25. B(6)=.2421751097243E-03
26. G(6)=.7884964267926E-07

```

HEAT (Cont)

```

C DO LOOP 400, INDEX L, DETERMINES NUMBER OF STATIONS TO BE ANALYZED
27. DO 400 L=1,2
C READ WIRE RESISTANCE IN OHMS, NUMBER OF THE DIRECT MODE READING
C CYCLE, AND THE 68 CHARACTER STATION TITLE.
28. READ 11,C1,N,(TITLE(K),K=1,17)
29. 11 FORMAT (F4.2,I2,I7A4)
30. PRINT 12,(TITLE(K),K=1,17)
31. 12 FORMAT (1H1,I7A4,/)
C INSERT DO 18 I=1,5 CARD, PLUS A C(I)= DESIRED VALUE CARD, IF ASSUMED
C VALUES OF THERMAL CONDUCTIVITY ARE TO BE USED.
C INSERT READ 16 STATEMENT IF THERMAL CONDUCTIVITY VALUES ARE TO BE
C READ IN AS DATA. USE CGS UNITS.
32. DO 18 I=1,5
33. C(I)=.0018
34. 18 CONTINUE
C DO LOOP 300, INDEX J, READS AND COMPUTES EACH OF THE 3 CYCLES
35. DO 300 J=1,3
C READ VOLTAGES FOR EACH CYCLE V(7) AND V(8) ARE BATTERY VOLTAGES
C AT BEGINNING AND END OF EACH CYCLE V(1) IS VOLTAGE READ FOR
C THERMISTOR NUMBER 1.
36. READ 20, (V(7),V(2),V(1),V(3),V(4),V(5),V(6),V(8))
37. 20 FORMAT (8F10.0)
C BL1 IS AVERAGE BATTERY VOLTAGE FOR EACH CYCLE USED FOR COMPUTATIONS
38. BL1=(V(7)+V(8))/2.
C ROUTING STATEMENT FOR COMPUTATION OF THE DIRECT READING CYCLE
39. IF (J.EQ.N) GO TO 144
C COMPUTE RESISTANCE OF REFERENCE THERMISTOR 2
C SUBTRACT C1 OHMS FOR CABLE RESISTANCE
40. R(2)=F(2)/(BL1/V(2)-1.0)-C1
C COMPUTE OTHER RESISTANCES AND TEMPS RELATIVE TO T2
41. I=1
42. R(I)=F(I)*(V(I)+V(2))/(BL1-V(I)-V(2))-C1
43. DO 30 I=3,6
44. R(I)=F(I)*(V(I)+V(2))/(BL1-V(I)-V(2))-C1
45. 30 CONTINUE
46. GO TO 148
47. DO 146 I=1,6
48. R(I)=F(I)/(BL1/V(I)-1.0)-C1
49. 146 CONTINUE
50. 148 DO 150 I=1,6
C COMPUTE TEMPERATURE FROM PARAMETERS
51. RLOG=ALOG(R(I))
52. T(I)=1/(A(I)+B(I)*RLOG+G(I)*RLOG**3)-273.16
53. 150 CONTINUE
54. PRINT 200,J,BL1
55. 200 FORMAT (20X,*CYCLE NUMBER *,I1,10X,
C*AVERAGE BATTERY VOLTAGE IN MILLIVOLTS =*,F10.3,/)
56. PRINT 222
57. 222 FORMAT (3X,*THERMISTOR*,4X,*VOLTAGE*,4X,*RESISTANCE*,4X,
+ *TEMPERATURE*,4X,*CONDUCTIVITY*,4X,*DELTA T*,4X,*GRADIENT/KM*,
+ 4X,*AVERAGE COND*,4X,*HEAT FLOW UNITS*,/)
58. DO 250 I=1,4
C COMPUTE DELTA T
59. D1=T(I)-T(I+1)
C COMPUTE GRADIENT/KM
60. G1=D1*5J00.
C COMPUTE AVERAGE CONDUCTIVITY BETWEEN ADJACENT THERMISTORS
61. A1=(C(I)+C(I+1))/2.
C COMPUTE HEAT FLOW USING AVERAGE CONDUCTIVITY VALUE
62. H1=50000.*D1*A1
63. PRINT 224,I,V(I),R(I),T(I),C(I)
64. 224 FORMAT (7X,I1,6X,F10.3,2X,F10.1,4X,F10.3,10X,F7.6)
65. PRINT 226,D1,G1,A1,H1
66. 226 FORMAT (70X,F10.3,4X,F10.1,8X,F7.6,6X,F10.2)
67. 250 CONTINUE
68. I=5
69. PRINT 224,I,V(I),R(I),T(I),C(I)
70. PRINT 260,V(6),R(6),T(6)
71. 260 FORMAT (7,5X,*WATER*,4X,F10.3,2X,F10.1,4X,F10.3,/)
72. 300 CONTINUE
C LOW POWER DISSIPATION IN MILLIWATTS
73. PL1=V(2)*V(2)*R(2)/((R(2)+C1)*(R(2)+C1))*0.001
74. PRINT 310,PL1,C1
75. 310 FORMAT (20X,*LOW POWER DISSIPATION IN MILLIWATTS =*,F5.3,
+ 10X,*CABLE RESISTANCE = *,F4.2,* OHMS*)
76. 400 CONTINUE
77. STOP
78. END

```

MONO LAKE SURVEY

HEAT (Cont)
Sample Data Sheet

STATION Base
1

POSITION Blue

DROP TIME 0915

DATE 5-16

Black Pt.

ON BOTTOM 0940

DEPTH 80'

METHOD Sextant

START MEAS. _____

OPERATOR GC, EW

ON DECK _____

LOW POWER !!! WAIT 10-15 minutes!!!

HIGH POWER
(ALWAYS IN DIRECT MODE)

MODE SWITCH VOLTAGE COMMENTS
POSITION

SWITCH VOLTAGE TIME COMMENTS
POSITION

D BAT TRIM TO .3999
D T-2 .2499
B T-1 -0.315
B T-3 - .15
B T-4 - .07
B T-5 + .375
B T-W -2.00
D RES 2.84
D BAT TRIM TO .3999
D T-2 .2499
BD T-1 .2496
BD T-3 .2497
ED T-4 .2498
ED T-5 .2503
ED T-W .2479
D BAT TRIM TO .3999
D T-2 .24995
B T-1 - 1.32
B T-3 - .145
B T-4 - .075
B T-5 + .375
D T-W - 2.04
D BAT .3999

BAT READ 12.826 .00 0955
T-2 7.841 15
T-1 7.817 30
T-3 7.812 45
T-4 7.818 00 0956
T-5 7.8265 15
T-W 7.720 30
BAT READ 12.808 45
T-2 7.8095 00
T-1 7.793 15
T-3 7.797 30
T-4 7.805 45
T-5 7.8165 00
T-W 7.709 15
BAT READ 12.800 30
T-2 7.801 45
T-1 7.785 00
T-3 7.790 15
T-4 7.799 30
T-5 7.810 45
T-W 7.703 00
RES
BAT 12.792 15

Sample Data Cards
1st card at top

IDENTIFICATION

IDENTIFICATION

IDENTIFICATION

IDENTIFICATION

HEAT (Cont)

Sample Output

BASE STA 16 MAY 80 FT

CYCLE NUMBER 1

AVERAGE BATTERY VOLTAGE IN MILLIVOLTS = 399.900

THERMISTOR	VOLTAGE	RESISTANCE	TEMPERATURE	CONDUCTIVITY	DELTA T	GRADIENT/KM	AVERAGE COND	HEAT FLOW UNITS
1	-.315	7695.0	4.950	.001800	.096	479.6	.001800	8.63
2	249.900	7721.1	4.854	.001800	-.032	-158.9	.001800	-2.66
3	-.150	7703.9	4.886	.001800	.059	296.9	.001800	5.34
4	-.070	7716.0	4.827	.001800	.013	63.3	.001800	1.14
5	.375	7752.9	4.814	.001800				
WATER	-2.000	7559.4	5.341					

CYCLE NUMBER 2

AVERAGE BATTERY VOLTAGE IN MILLIVOLTS = 399.900

THERMISTOR	VOLTAGE	RESISTANCE	TEMPERATURE	CONDUCTIVITY	DELTA T	GRADIENT/KM	AVERAGE COND	HEAT FLOW UNITS
1	249.600	7696.2	4.947	.001800	.093	463.5	.001800	8.34
2	249.900	7721.1	4.854	.001800	-.043	-212.7	.001800	-3.63
3	249.700	7704.8	4.897	.001800	.064	318.5	.001800	5.73
4	249.800	7713.5	4.833	.001800	.024	122.4	.001800	2.20
5	250.300	7755.0	4.809	.001800				
WATER	247.900	7559.4	5.341					

CYCLE NUMBER 3

AVERAGE BATTERY VOLTAGE IN MILLIVOLTS = 399.900

THERMISTOR	VOLTAGE	RESISTANCE	TEMPERATURE	CONDUCTIVITY	DELTA T	GRADIENT/KM	AVERAGE COND	HEAT FLOW UNITS
1	-.320	7698.7	4.941	.001800	.097	485.0	.001800	8.73
2	249.950	7725.2	4.844	.001800	-.031	-153.5	.001800	-2.76
3	-.145	7713.4	4.874	.001800	.057	266.1	.001800	5.15
4	-.075	7719.7	4.817	.001800	.014	68.7	.001800	1.24
5	.375	7757.0	4.803	.001800				
WATER	-2.040	7560.2	5.338					

LOW POWER DISSIPATION IN MILLIWATTS = .008

CABLE RESISTANCE = 2.84 OHMS

VIII.

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APPENDIX "A"

SELF-HEATING CALIBRATION FOR THERMAL CONDUCTIVITY MEASUREMENTS

Calibration of each probe in sediments with several different known thermal conductivities is required because a theoretical solution to the temperature rise of a thermistor implanted in the probe is not possible. Earlier attempts used hand-mixed batches of illite and water to simulate sediments, but problems of phase separation caused vertical inhomogeneities in these muds. To solve this problem, a more sophisticated system for homogenizing the mud has been developed, utilizing a small drilling mud pump. An open container serves as an intake sump for the mud and a convenient place for the addition or subtraction of mud, water, or dry illite required to change the thermal conductivity of the mud. The pump output flows through a horizontal tube containing the probe being calibrated, then into a return tube to the sump. A large needle probe of the type discussed by Von Herzen and Maxwell (1959) is included in the return tube. The needle probe measurements will be compared with water content measurements to provide a check on the accuracy of the measurements and the validity of the empirical relationship given by Bullard (1963).

By comparison with temperature rise curves in several muds of different thermal conductivities, a reasonable value for thermal conductivity should be obtainable from actual in situ temperature rise data. If possible, a simple procedure for going directly from the raw high power (self-heating) data to the thermal conductivity value for any particular thermistor will be developed. If this is not possible, the more time-consuming comparison of calibration curves with the actual in situ temperature rise curve to yield the thermal conductivity value must be used, followed by keypunching this value for input into the program which computes heat flow values.

At present, the mechanical side of the calibration apparatus is functioning well. The main task remaining before actual probe calibration can begin is testing of the needle probe to insure proper functioning and accurate thermal conductivity measurements. A solid of known thermal conductivity will be molded around the needle probe for this test. Successful testing will be followed by the actual calibration of the probes. Next comes the work of reducing the calibration data, analyzing the results, and developing the procedure for obtaining thermal conductivity from the field data. The final step is application of the procedure to the field data to yield the heat flow values at each station.

APPENDIX "B"

THERMISTOR CALIBRATION PARAMETERS

<u>NUMBER</u>	<u>ALPHA (A)</u>	<u>BETA (B)</u>	<u>GAMMA (G)</u>
Probe with rod 010			
1	.1405619148524E-02	.2366340159203E-03	.1013227429485E-06
2	.1400805645116E-02	.2375490614880E-03	.9711314628007E-07
3	.1396225549155E-02	.2382998351121E-03	.9413025559497E-07
4	.1379583760132E-02	.2412683442044E-03	.8102214203783E-07
5	.1401780201060E-02	.2372679173381E-03	.9849340173962E-07
WATER	.1371738978022E-02	.2421751097243E-03	.7884964267926E-07

Probe with rod 011			
1	.1290647618792E-02	.2348202092703E-03	.9673451774354E-07
2	.1249995093676E-02	.2416772109565E-03	.6817110192760E-07
3	.1214682809698E-02	.2475705089771E-03	.4391886558117E-07
4	.1272985554749E-02	.2379463392318E-03	.8363514723076E-07
5	.1226739538178E-02	.2458600084292E-03	.5004747128655E-07
WATER	.1171200043931E-02	.2554638622386E-03	.6548372013522E-07

Rod 012			
1	.1397467250189E-02	.2376339545929E-03	.1016678044262E-06
2	.1370711920778E-02	.2428325587475E-03	.7388828797299E-07
3	.1404050208335E-02	.2368421525552E-03	.1023213537652E-06
4	.1387054317792E-02	.2401158906457E-03	.8516856668019E-07
5	.1392065358256E-02	.2389819692031E-03	.9119815532000E-07

Rod 013			
1	.1386392334153E-02	.2401841635747E-03	.8381431091496E-07
2	.1388272794840E-02	.2398723507279E-03	.8470343025301E-07
3	.1386845439040E-02	.2400964157659E-03	.8550521106501E-07
4	.1383970486954E-02	.2404899158907E-03	.8334025849897E-07
5	.1385717198109E-02	.2402488892484E-03	.8415428168075E-07

APPENDIX "C"

FIXED RESISTOR VALUES (OHMS)

<u>Number</u>	<u>Unit 010</u>	<u>Unit 011</u>
1	4636.1	4637.0
2	4636.2	4637.1
3	4636.3	4637.3
4	4636.6	4637.4
5	4636.7	4637.7
WATER (6)	4636.8	4637.8

THERMAL PROBE STUDY

of

CLEAR LAKE

Roger C. Martin, Ph.D.

State Lands Division

August 30, 1976

CLEAR LAKE GEOTHERMAL GRADIENT STUDY

Summary

A one-meter temperature gradient survey method was tested at Clear Lake, California, as a submerged land geothermal exploration tool.

Clear Lake is a large, warm, shallow, practically nonstratified body in a high volcano-tectonic collapse setting with a Mediterranean climate. Average and maximum depths are 10 and 17 meters, respectively, and annual bottom-water temperature ranges from 6 to 24.5° C. Temperature measurements were carried out during an 11-day period in late April and early May. The onset of clear skies and warm spring weather about May first raised lake temperatures abruptly and introduced strong thermal noise in the sediment thermal gradient data.

Despite the onset of insolar noise, four thermal anomalies were discerned. The anomaly areas have not been tested by other geophysical means or by drilling, but all are adjacent to areas with known thermal springs or volcanic effusives less than 0.4 million years old with evidence of craters or other vent activity less than 100,000 years old.

The method of data interpretation was determined by the strong insolation effects on the upper probe thermistors. Use of the full one-meter gradient data was discarded in favor of a combination of simple 80 cm. depth temperatures, and short 20 cm. gradients measured at the bottom end of the probe.

Introduction

Clear Lake was chosen as one of the test sites for the one-meter probe exploration method because of the likelihood of finding measurable geothermal anomalies. Recent thermal gradient investigations by the Geological Survey in eight drill holes in the lake (Sims & Rymer 1975) did not reveal unusual geothermal gradients. Nevertheless, the geologic setting, which includes recent tectonic and volcanic activity, and the existence of known hot springs and wells near the shores of the lake at Sulfur Banks, Soda Springs and Mt. Konocti offered an incentive for further more detailed exploration for geothermal surface phenomena.

At the outset it was recognized that, whereas the geology of Clear Lake appeared favorable for testing a geothermal exploration technique, other physical qualities of the lake would present real challenges. The most serious are the shallowness of the lake (average depth about 10 meters) and a relatively warm year-round climate. Apparently precise measurements of normal, continental heat flows have been measured in the bottom sediments of deep, higher latitude lakes. These lakes experienced freezing winters. Surface waters, cooled to the region of maximum density around 4° C. tend to form a cold dense layer (hypolimnion) which maintains a nearly anathermic state and temperature of approximately 4° C. year around. Summer heating of these lakes may warm only a shallow surface layer (epilimnion) and a gradational thermocline between it and the cold bottom layer.

FIGURE 1

FIGURE 3

CLEAR LAKE

*GEOTHERMAL GRADIENT STUDY
MEASURING SEQUENCE IN DAYS*

FIGURE 4

CLEAR LAKE

REFERENCE STATION 1, TEMPERATURE
VARIATIONS WITH TIME MEASURED
WITH THERMISTORS IN BRIDGEMODE. +

LEGEND

THERMISTOR	DEPTH
T1	80 CM
T2	60 CM
T3	40 CM
T4	20 CM
T5	10 CM
TW	WATER/SEDIMENT INTERFACE

FIGURE 5

The thermal stability of the cold dense layers, like that of deep ocean bottoms, provides an environment in which even very feeble geothermal heat flows can be measured in the bottom muds.

No such stratification, however, was found at Clear Lake. Preliminary studies by Goldman & Wetzel (1963) and others concerned with algae and related biological studies indicated that lake temperatures range from 7.5 to 24.5° C. and thermal stratification exists only weakly and intermittently in the summer months. Most of the lake is less than 10 meters deep; hence, surface and bottom waters are rapidly mixed by wind-induced circulation.

A heat-flow study of eight drill holes in the Clear Lake bottom sediments by the U. S. Geological Survey showed empirically that the annual solar heating effects penetrated to a depth of about 10 meters beneath the lake bottom (Tom Urban, pers. comm.). Theoretical calculations by the Lawrence Berkeley Laboratory in the previous section treating the lake as a sinusoidally varying heat source indicated that mud temperature 80 cm. below lake bottom might vary 10° C. annually. Part of the computer-programmed data using assumed conductivity and diffusivity values are plotted in Figure 1. Corresponding empirical data obtained at one of our control stations show approximate agreement with the theoretically computed values.

Field Operation

In order to minimize the effects of thermal noise caused by insolation affecting the detection of geothermal heat flows, the field survey was planned to accomplish water and subsurface temperature measurements in the shortest possible time. Also, because of fragility problems of the prototype fiberglass thermistor probes, the lake was divided into areas of differing priority and effort was concentrated first on adjoining areas of greatest promise in case instrument breakage or malfunction might preclude completion of the entire survey in the time available. This procedure worked out well, for the two eastern arms of the lake bordering the Sulfur Bank, Borax Lake and Konocti Bay potential thermal areas were completed during the first week, when measured insolation effects were minimal.

The base of operations with boat docking facilities was set up near the junction of the two eastern arms and the main western body of Clear Lake. In order to monitor the effects of solar heat flux and to provide correction to measured data, three principal control stations were established, two near the operating base in the east arm of the lake (Stations 1 and 2) and one to the west in the main part of the lake (Station 16). Three other stations (35, 41 and 42) were monitored occasionally to verify the validity of possible unexpected thermal changes at the principal control stations.

Measurements were made at stations spaced about one kilometer apart, using the standard 1000-meter Universal Transverse Mercator grid system. In the northwest part of the main lake body a two-kilometer grid was used. Penetration was usually no problem for the lake bottom consists of fairly uniform low density dark gray saprophyllitic mud. The mud is dominantly mineral silt with a high organic colloid and clay content. The mud is dark gray and remarkably similar over the entire lake bottom. Penetration problems were experienced only in the extremities of the eastern arms of the lakes, e.g., near Rattlesnake and Indian islands and in shallow areas off points, e.g., Monitor Point. There impenetrable gravel was found at the lake bottom or below a thin layer of mud.

Data Analysis

Thermal Noise

The nonstratified nature of Clear Lake is apparent in Figure 2 in which bottom water temperatures of 40 different stations are plotted as a function of station depth. The data, measured during the last week of April, show that at depths between 18' and 52' (the maximum depth encountered) temperatures were distributed in a narrow range between 13° and 13.6° C. The figure shows a very gradual gradient of 0.5° C. in this interval, warmer at the top. Bottom temperatures of shoal areas less than 18' deep show progressive warming inversely with the depth to a maximum of 14.8° at a depth of 10.5'. Figure 2, of course, does not depict thermal gradients in a vertical column, but shows a composite of bottom temperatures at widely dispersed stations. It illustrates the result of a lake undergoing solar heating with mixing of warm surface and cooler bottom waters more rapidly in the shallow portions.

The warmest station, 20, is anomalous; it is located on an alignment of springs. The effects of insolation are shown strongly in Figure 2 by the control Stations 1 and 2. These points at one- and two-week intervals after the initial measurement are repeated, showing progressively higher temperatures. The bottom water temperatures increased more than 2° C. each week during the study. Thus the need for rapid completion of work in specific segments of the lake and continuous monitoring of thermal changes at selected control stations is apparent.

Areal distribution of uncorrected bottom temperatures, T_w , over the entire lake (Figure 3) shows a pronounced increase in temperature at the shallow margins and toward the northwestern end of the lake due to progressive insolation. This is borne out by Figure 4, which shows the succession of areas surveyed during the field operation from day 1 to day 14. Note the remarkable coincidence of warm areas shown by the uncorrected data and the areas measured in the last few days of the survey (e.g., days 12, 13 and 14) when cumulative thermal noise was greatest. Fortunately, the thermal regime during the first six days of the survey was relatively stable and has required little correction of thermal drift.

Time-Temperature Variations at Control Stations

During the first eight days of the field operation the five submerged thermistors indicated a simple and consistent thermal gradient of about 1° C. between the upper (cooler) and lower (warmer) thermistor. As time progressed, the uppermost thermistor, T_5 , began responding to the increased insolation, showing that the mud 10 cm. below the water interface was gaining temperature, lagging about $2\frac{1}{2}$ days behind the increase in bottom water temperature. T_4 , at a depth of 20 cm. also responded, with a lag of four to five days. By the end of the field survey, 11 days after the abrupt lake water increase, T_4 had risen 0.8° to equal the temperature of T_3 , and T_5 had risen 1.25° C. to equal that of T_1 . During this period, all thermistors registered a rise in temperature. As the upper temperatures approached that of the lower, thermal gradients decreased and passed into a complex state. By mid summer it will doubtless be reversed. Initial thermal gradients measured late in April were of the order of 0.015°/cm., equivalent to a geothermal heat flow of 27.7 heat flow units (if the heat were of telluric origin) as measured between T_1 and T_2 . By the end of the field operation, this gradient was reduced to .009°/cm., equivalent to a geothermal heat flow of 16.26 heat flow units, and the upper thermistors were registering strong negative apparent heat flows. Thus, gradient changes at the control station indicate clearly the dominance of solar heat flux.

At Control Station 2, which is just off Indian Beach, one km north of Station 1, almost identical results were found (Figure 6). Both stations are at a depth of 37 feet near the junction of the east and southeast arms of Clear Lake. These are narrow, steep-sided drowned valleys with maximum depth of about 50 feet.

The floor of the western or main basin of Clear Lake has a broad, saucerlike shape. Maximum depth is less than 30 feet. Control Station 16 at a depth of 27 feet is probably representative of the center part of the lake. As shown in Figure 7, the thermal regime and insolation effects are like those of Stations 1 and 2, but more pronounced. Cross-over of T_5 and T_4 temperature curves occurred two days earlier than at Station 1, and by the end of the field survey, even the T_3 curve has crossed the T_2 curve. The plotted temperature data appear less consistent than those of the other control stations, especially the water bottom temperature, T_w . This scatter of data was probably the result of thermal inhomogeneity caused by a submerged spring. Existence of the spring at or very near Station 16 was not apparent until the 13th day of the survey (May 9, 1976) when ebullition of bubbles revealed an east-west alignment of gas seeps. The most vigorous gas seep appeared within ten meters of the Station 16 buoy. Such gas seeps are relatively common in Clear Lake and are an intermittent characteristic of many submerged springs (Sims & Rymer 1976). The gas is believed to be carbon dioxide and, to a lesser extent, methane.

T_1 and ΔT_1 Exploration Parameters

In analyzing both the local and regional variations of the data represented in Figures 5, 6 and 7, it quickly became apparent that the upper thermistor temperatures T_4 and T_5 were too unstable for use as a practical geothermal exploration parameter. Hence the original intent of using the entire one-meter probe gradient, i.e., measuring the thermal gradient between thermistors T_1 and T_5 proved impractical, even by applying correction factors to the rapidly increasing T_5 temperatures. The gradients computed between thermistors T_1 and T_3 appeared only marginally useful because of gradually increasing insolation at depths measured by the T_3 thermistor.

T_1 , the lowest thermistor, shows the greatest stability, and the parameter ΔT_1 , which is the difference between temperatures T_1 and T_2 , measured 20 cm. apart, has proven to be the most stable gradient value.

The relation of T_1 and ΔT_1 variations is shown in Figure 8 where Station 2 data are plotted. Because of a greatly expanded vertical scale, the T_1 curve, which appears fairly constant in Figure 6, appears as a continually ascending curve in Figure 8, and data points appear more scattered.

The ΔT_1 or T_1 - T_2 data plot as a descending curve because of the progressive warming and approach of T_2 relative to T_1 . The ordinate scale of ΔT_1 is on the left side of the graph, whereas that for T_1 is on the right.

Use of Control Data for Correction of Time-Related Variations

The T_1 curves of Figures 5, 6, 7, and 8 display for each control station smooth variations in temperature. These regular variations have allowed simple correction of data to an arbitrary day baseline.

The ΔT_1 curves for three control stations are not so consistent, however. The ΔT_1 curve for Station 16 (Figure 9) shows a scatter of points in the May 6

through 10 interval suggesting no consistent change in ΔT_1 , but with a possible change in values before and immediately after. Stations 41 and 42, also in the main lake body as Station 16, show falling ΔT_1 values consistent with the curve in Figure 8, but because the data are too widely spaced, they do not either confirm or prove the irregular trend shown by the curve of Figure 9. Confirmation of the nature of the curve is suggested, however, in the data from Control Station 1 in Figure 10. Here, the ΔT_1 values define a broken or irregular curve having some characteristics of both Station 2 and Station 16 curves; that is, gently declining values of ΔT_1 the first week, followed by constant (but scattered) values the second week with an abrupt fall-off on the last two days.

Evaluation of Bridge and Direct Modes of Instrument Operation:

The difference between "bridge" and "direct" mode data is explained in the preceding section describing instrumentation. In the field, temperature measurement followed an arbitrary procedure of measuring each thermistor's resistance twice in the "bridge mode" and once in the "direct mode". The result is three very close temperature measurements. In case of an error, it is readily apparent which of the three measurements is wrong. In the "direct" mode the resistance of each thermistor is measured using the conventional Wheatstone bridge method. In the "bridge" mode, the resistance of each thermistor (except T_2) is measured relative to that of the T_2 thermistor; i.e., T_2 is substituted for one of the "direct" mode resistors in the Wheatstone bridge. This "bridge" mode was chosen in order to more precisely determine the minute temperature gradients $\Delta T_1, \Delta T_2, \Delta T_3$, measured across 20 cm. height differences. True temperature accuracy was regarded as less important than the gradients. Temperatures can be measured by either the bridge or direct mode, but the direct mode is considered more reliable by design.

In practice, two bridge mode readings are made, the second one (cycle two) to serve as a comparative check on the first (cycle one), mainly to determine if the submerged thermistors have rested in place long enough to have reached equilibrium with the sediments.

Comparison of these data is possible in Figure 11, where T_1 variation is plotted on an expanded temperature scale so that very small temperature differences may be seen. In most cases the three measurements group close together. Scatter of temperatures from a smooth curve is greater for the groups (measured on a given day) than for individual measurement modes. Apparently, the greatest errors are determined by geologic variables (i.e., placement of the probe in a slightly different position at the control station where sediment thermal characteristics may be different).

A very real source of error occurs from not allowing sufficient time for the probe to reach thermal equilibrium with the sediment. This would be indicated by relatively great differences between the bridge mode temperatures. Insertion of the probe creates friction-induced high initial temperatures. The bridge mode cycle 1 temperature measurements, indicated by dots on the graph, should be higher if different from the other bridge or direct measurements because it is always the first temperature measured. Hence the probe may be less at equilibrium with the sediments than at the time of the succeeding measurements. In the field, if large differences were noted between the bridge mode cycle 1 and cycle 2 measurements, measurements would cease for five or ten minutes to allow better equilibration, and repeat measurements would be made later.

Other than this time-sequence factor there is no reason to expect bridge mode cycle 2 measurements to differ from the direct-mode measurements, if instrument calibration is perfect in each case.

In practice, all three types of measurements grouped close enough together so that consistent use of any one type of measurement would easily define the natural temperature anomalies encountered in this study. (They commonly grouped within 0.02°C . The greatest error, 0.078°C ., occurred on a hurried measurement at Station 2 of 10 May - Figure 8.) The first measurements taken (bridge mode cycle 1) depicted as small solid dots in Figures 8 and 11 did tend to be slightly higher than the others. At Station 2 (Figure 8) these temperatures were high in three cases, but practically coincided with one of the other measurements in three cases. At Station 1 (Figure 11) these temperatures were high in four cases, low in two, and coincided with other measurements in five cases.

Since three-place accuracy of the temperatures measured are unknown, evaluation of the direct and the bridge mode cycle 2 measurements is essentially limited to comparison with the other measurements. With both, coincidence with other measurements is fairly high. At Station 1 (Figure 11) the direct mode temperatures showed near coincidence or a median position in 7 out of 11 cases, and the bridge mode cycle 2 yielded eight coincident or median temperatures out of 11. The bridge mode cycle 2 measurements were low in three cases, with no highs, whereas the direct measurements were high in four cases with no lows. Similar results were found at Station 2 (Figure 8). Bridge mode cycle 2 measurements were coincident in four cases and low in two. Direct mode measurements were coincident or median in five of six measurements, with one low value.

In summary of the above data, the first measurements taken (bridge mode cycle 1) were as expected, highest, with fewest coincident and median values (5 of 17). The direct mode data tend to be comparatively high but with a high proportion of (12 of 17) coincident or median values. The bridge mode cycle 2 data tend to be low, with an equal proportion of coincident and median values. The practical insignificance of these two data types can be seen by comparing the six thermistor temperature/time curves of Control Station 1. The data plotted in Figure 5 is bridge mode cycle 2; in Figure 12 it is direct mode. The most conspicuous difference occurs in the T_w curves at April 28. The bridge mode T_w value was found to be wrong due to human error; consequently, no T_w datum is plotted in Figure 5.

Evaluation of ΔT_1 values obtained at all the control points (data plotted in Figures 8, 9 and 10) show that the bridge mode cycle 2 data is the most consistent, with 28 median and coincident values, two high and two low. The direct mode, which was not designed for these gradient ($T_1 - T_2$) measurements, showed the greatest scatter, 21 coincident and median values, 7 high and 2 low.

Based upon these findings, interpretations of the geothermal data, and construction of the Clear Lake thermal properties maps, has preferentially utilized the direct mode data for T_1 temperatures and bridge mode cycle 2 data for ΔT_1 values.

Findings

T₁ Distribution, Uncorrected

Uncorrected temperatures 80 cm. beneath the lake bottom are plotted on the Clear Lake map of Figure 13. Temperatures ranged from 12.76° C. to 23.86° C., but the great majority were between 12.8 and 14.4° C. Four anomalies or hot spots are evident beneath the southeast arm of the lake and a fifth at Soda Bay at the southernmost part of the main lake basin.

The most prominent anomaly is at Oak Cove, anomaly "A" of Figure 13, where the highest sediment temperature measured (23.86° C.) during the survey was obtained. This anomaly is very near the north shore of the southeast arm of Clear Lake, not far from the Borax Lake graben area where surface geothermal activity is known. Anomaly "A" is discussed in greater detail in the next section.

At anomaly "B", off Point Lakeview, a temperature of 14.68° C. was measured. It is adjacent to a complex of young dacite flows and domes. South and southeast of the anomaly are a Recent explosion crater and Thurston Lake, formed in a volcano-tectonic depression and impounding lava flows. According to preliminary mapping by Hearn, et al. (1975), anomaly "B" is partially circled by five presumed vents from which the dacite lavas and pyroclastic rocks were erupted.

Anomaly "C" is immediately offshore of Little Borax Lake, a volcanic vent at which the most recent activity was a phreatic explosion creating the crater occupied by the lake. A second volcanic vent in the anomaly "C" area is postulated by Hearn, et al. (1975), beneath Clear Lake midway between the Little Borax Lake isthmus and Fraser Point. These vents are aligned with a larger Recent crater, forming Horseshoe Bay, and a line of offshore gaseous springs extending from Fraser Point to Wheeler Point. These craters are believed to be the vents for the well bedded tuff and lapilli beds mantling Mt. Konocti and the Buckingham Peninsula (Hearn, et al. 1975). The maximum sediment temperature measured here (depth of 80 cm.) was 14.30° C. Nearby stations registered warmer than normal temperatures of about 13.53° C.

At Soda Bay (anomaly "D" of Figure 13) a sediment temperature of 14.03° was measured about 60 meters from Big Soda Spring. This temperature is not as high as might be expected in view of its proximity to a known thermal spring, and high ambient lake water temperature (16.6° C. to over 17° C.). Water circulation is apparently restricted in Soda Bay. Besides the relatively high water temperature here, we observed the most advanced stage of algae growth at that time of year, early May.

Anomaly "E", at the extreme southeastern tip of Clear Lake, is based upon a single measurement point (Station 30) at a shallow depth of 3 meters (10.5 ft.). The entire end of the southeast arm of the lake is shallow and underlain by gravel as well as mud, and Station 30 was the southernmost point where penetration was achieved. Because of the shallowness of the lake here and the likely rapid response to solar heating, it is tempting to discount the relatively high sediment temperature (14.37° C.). Unlike the Soda Bay station (anomaly "D"), however, no unusually high water temperatures were noted. Station 30 lies on the southeast margin of the same young (less than 0.4 million years) dacite domes and flows associated with the Point Lakeview ("B") thermal anomaly. It is also in near alignment with warm gaseous springs mapped off Luebow Point by Sims and Rymer (1976).

The "raw" 80 cm. sediment temperatures also show possible weak anomalies west of Clear Lake Oaks ("F") in the eastern or "Oaks" arm, and near Nice ("G") at the north end of Clear Lake. No evidence of recent volcanism is known in those areas.

Expected thermal anomalies near Sulphur Banks, a site of thermal wells and current hydrothermal activity, were not found. Because of high local relief, the lake bed consists of gravel and rock debris; consequently, no probe penetration was achieved within 1.5 km of Sulphur Banks.

T₁ Distribution, Corrected for Seasonal Drift

Figure 14 shows 80 cm. sediment temperature distribution partially corrected for the rapid seasonal warming of the lake. These data show a simpler subsurface heat distribution than Figure 13. The "A" anomaly remains prominent and appears to extend southward to the "E" anomaly, parallel to regional and local structural trends.

The Point Lakeview anomaly adjacent to the Thurston Lake dacite extrusions and the Little Borax Lake anomaly also persist in the corrected data of Figure 14. The impression of warm anomalies ("B", "C" and "D") partially surrounding volcanic Mt. Konocti shown in Figure 13 changes to one of separate, northwest-aligned anomalies in Figure 14 as the Soda Bay anomaly of Figure 13 has not survived the seasonal correction process. This is probably the most significant difference between the two figures.

Other differences are the diminution of apparent thermal anomalies west of Clear-lake Oaks and at Nice (Figure 13 anomalies "F" and "G", respectively). A cold anomaly appearing in Figure 14 near the junction of the east and southeast arms of Clear Lake is probably the result of the drift correction applied to a measurement taken out of sequence with the others, on the last day of the survey. This may illustrate the imperfection of the correction process. Further work is planned, reducing the degree of drift correction.

Thermal Gradient, or ΔT_1 Distribution

The original design of this exploration method planned for measurement of thermal gradients across the full one-meter length of the thermistor probe. Thermistors at 20 cm. intervals on the probe showed, however, that the upper half-meter of sediment was subject to relatively rapid temperature changes during the period of data collection. In this case, the upper thermistors were apparently responding to accelerated seasonal (spring) warming. At the beginning of the field operation, temperature gradients of the order of 0.31° C. were obtained between 60 and 80 cm. depth levels, and 0.22 between the 20 and 40 cm. depth levels. Two weeks later those values had changed to 0.19 and 0.00, respectively. All of the ΔT values were drifting downward, but those for the lowermost thermistors were changing more slowly and, hence, were more amenable to seasonal drift correction. Further, it was judged that the thermal gradients measured across the lowest 20 cm. interval were far more consistent than those measured between the lowest and highest thermistors on the probe.

Heat Flow

Assuming a uniform thermal diffusivity of 0.0020, the heat flow computed from the initial ΔT_1 figure of 0.31 amounts to 28 heat flow units, which is about 19 times normal in continental areas (one heat flow unit = 1×10^{-6} calories/cm²/sec.).

Similar figures were obtained in nearly all parts of the lake, indicating that these abnormally high heat flows are the result of winter cooling of the sediments and lake water, hence are solar rather than geothermal phenomena.

The lakewide distribution of drift-corrected ΔT values for the 60 - 80 cm. depth levels is plotted in Figure 15. These values, too, indicate marked anomalies at Oak Cove ("A"). Point Lakeview ("B") and offshore of the Little Borax Lake area ("C"). An interesting anomaly is indicated in the middle of the lower or southeast arm of the lake, just west of "A". Other interesting but weak anomalies are shown at "F" and "H". The latter anomaly extends along a line of gaseous springs (see Sims & Rymer 1976) extending from the Narrows northwestward toward Nice. As can be seen in Figure 13, no unusually warm temperatures were measured along this alignment. Further work in this area might profitably be directed toward examining the thermal properties of the sediments which may have been affected by the spring activity.

Oak Cove Geothermal Anomaly

On finding a T_1 temperature (23.86° C.) fully 10° warmer than normal, additional stations were established and measured in order to determine the extent and nature of this anomaly. As shown in Figure 17, the anomaly is relatively small; it is centered about 350 m. offshore, and sediment temperatures higher than 14° C. extend over an area at least 0.7 km across.

The pattern of high sediment temperature is shown also by ΔT data (Figure 19). These data also indicate an anomaly about 0.7 km across centered in Oak Cove. The maps also show agreement on the weaker Point Lakeview anomaly to the southwest.

As in the regional maps (Figures 14 and 15) the T_1 data (Figure 17) suggest a weak continuation of the Oak Cove anomaly to the Indian Island area at the southeast end of the lake, but the ΔT data (Figure 19) shows a separation of the two anomalies.

In order to determine if the Oak Cove anomaly is simply a submerged hot spring, bottom water temperatures were analyzed. Ambient water bottom temperatures in the middle of the arm were 13.14 to 13.40° C., with warmer temperatures in shallow shoreline areas. Maximum water bottom temperature at the center of the Oak Cove anomaly was 17.13° C., but at stations less than 100 meters distant, temperatures of about 13.7° C. were measured. These slightly high temperatures are probably more a function of shallow conditions than to mixing of hot spring waters. The limited extent of water temperatures over 14.00° C. suggest that a hot or warm spring probably issues forth near Station 35, but its discharge is not great. The wider distribution of warm sediment temperatures indicates that the Oak Cove anomaly, though small, is more than a hot spring, and its proximity to the Borax Lake graben (the southern part of which is shown by the depression contour at the northern margin of Figures 17, 18 and 19) suggests it is associated with the recent faulting, volcanism, and current geothermal activity there.

Related Studies

In 1973 the U. S. Geological Survey performed a core drilling project on Clear Lake utilizing a barge-mounted drilling rig. Eight holes were drilled ranging in depth from 14 meters to 115 meters. Sedimentologic studies (Sims & Rymer 1975) and heat flow studies were performed but the latter have not been released.

According to Mr. Tom Urban of the U. S. Geological Survey (pers. comm.), relatively low or normal heat flows ranging from 1 to 2.5×10^{-6} cal/cm²/sec) were obtained (typical values in active geothermal areas range from 6 to 12×10^{-6} cal/cm²/sec). Thermal noise due to insolation was evident in the upper 30 to 40 feet of the lake sediments; but below that depth thermal gradients appeared linear. For calculation of precise geothermal heat flows some concern was felt for possible deep thermal noise caused by Holocene climatic changes, and by raising of the lake level in 1915 by an impounding dam, which now regulates the level of Clear Lake.

Urban also measured a thermal profile across the main or west basin of the lake in September of 1973. This profile, 10 to 15 feet deep, showed isotherms parallel to the lake bottom, with temperatures between 15° and 20° C.

Figure 16 shows the distribution of the U.S.G.S. core holes. Note that none of the holes are located in any of the anomalies found in this one-meter probe study. Hole 7 had the highest gradient measured, with 2.5 heat flow units.

Cores from hole 7 (Sims & Rymer 1975) showed that the southeast arm, now the deepest part of the lake, was an open marsh prior to 11,000 B.P., and that gradual subsidence has occurred since that time, evidently associated with late volcanic activity and magma withdrawal.

In contrast to the "cold" findings of the U.S.G.S. study, temperatures of 77° C. have been measured at the 300-foot (91 m) level of Sulphur Bank Mine (Nielson et al. 1976). In the early 1960s four exploratory holes were drilled within a few hundred yards of natural solfateras, mercury mineralization and hydrothermal alteration. The geothermal holes ranged from 100 m to 1,219 m deep and encountered abundant flows of hot water as high as 204° C. The waters were charged with CO₂ and were rich in borates and other minerals.

Conclusions and Recommendations

The feasibility of this method as a geothermal exploration tool would not likely be challenged in a merimictic or similar lake with thermally stable bottom conditions. Results obtained in Clear Lake under rapidly changing water temperatures is encouraging. The validity of the distribution of thermal anomalies found with the one-meter thermistor probe is supported by an abundance of geologic and hydrologic data. These include recent volcanic features bordering the southeast arm of the lake, hot spring activity on the northeast slope of Mt. Konocti, Borax Lake and Sulphur Bank, and even the increasing concentration of boron toward the southeast end of the lake. Because the outlet of Clear Lake is at the extremity of the southeast arm and the principal streams flow into the lake in the northwest portion, the natural water flow is generally southeastward across the lake. Whisman et al. (1966) found that the boron content increases progressively from The Narrows southeastward. This supports the contention that thermal springs (which typically have a high boron content) are discharging at Soda Spring, Sulphur Bank and the anomalies cited in Figure 13, particularly those near Little Borax Lake and Borax Lake (Oak Cove).

For further work on this or similar shallow warm lakes, late winter or early spring should be favored for field measurements unless more research on data correction is intended. At Clear Lake the one-meter probe usually experienced easy penetration in deep ooze and mud or practically no penetration at all in rocky or gravelly areas. It is felt that a longer, $1\frac{1}{2}$ or 2-meter probe would have performed

satisfactorily at Clear Lake, and provided better, more stable temperature data. The Laurence Berkeley Laboratory workers experienced unforeseen problems in their efforts to measure in situ conductivity and diffusivity of the sediments. Hopefully, this work will be continued for these thermal properties would be of value in interpreting many of our observed temperature anomalies.

Acknowledgements

This study profited by stimulating discussions and helpful advice from Edward E. Welday of the State Lands Division and Dr. Pat Wilde and John Oldson of Laurence Berkeley Laboratory and Dr. Tien-chang Lee of University of California, Riverside. The field operation was ably assisted by State Lands Division personnel Grover Crow, Don Moore, Vidmantas Duda and David Gonzales, and drafting of maps and figures by Kenneth Larson.

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FIGURE 14

INDEX MAP OF CLEAR LAKE SHOWING LOCATIONS REFERRED TO
IN TEXT AND DISTRIBUTION OF U.S.G.S. COREHOLES (Sims and Rymer
1975).

FIGURE 16

FIGURE 17. OAK COVE GEOTHERMAL ANOMALY, SEDIMENT TEMPERATURE AT 80 CM DEPTH.

FIG. 19. OAK COVE GEOTHERMAL ANOMALY SHOWN BY PLOT OF ΔI ($T_1 - T_2$ DEPTHS OF 60 & 80 CM)

**Thermal Probe Study
of
Mono Lake, California**

by

**Edward E. Welday
Senior Marine Geologist**

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SUMMARY

Mono Lake was selected for a geothermal study because of the presence of young volcanic rocks in a basin containing a moderate thickness of water-saturated sediments. Thermal phenomena are common in the basin and numerous hot or warm springs are located around the lake and on the islands in the middle of the lake.

A thermal study of the lake was made during May 1976 using a six thermistor lightweight probe that penetrates a maximum of about 135 cm in the sediment. The probe was operated from a 16-foot outboard-powered boat using a three-men crew. Sediment and water column measurements were made at 70 stations using a one mile interval grid pattern for 58 stations, and 12 stations were made near gas seeps, hot springs, or other points of interest. Repeated measurements were made at a base station, and numerous measurements were made in the water column. The measuring instruments are not direct reading and temperatures must be computed, calculated or estimated from tables.

Over most of the lake, the bottom water and the bottom sediment were nearly the same temperatures with the bottom water averaging about 0.2 C warmer than the sediment. The average thermal gradient in the upper meter of sediment extrapolates to about 0°/km and over 60 percent of the stations have thermal gradients between +200°/km and -200°/km.

Three areas with anomalously warm positive thermal gradients were measured. The area with the highest gradient is near the very young volcanic rocks on Paoha Island. Four stations within about one-fourth mile of Hot Springs Point had thermal gradients approaching 1000° to 2000°/km. Weaker positive gradients were found near Negit Island and southeast of Paoha Island suggesting that a narrow zone of anomalous positive thermal gradient extends from Black Point, through Negit and Paoha Islands following the belt of young volcanics to the

southern shore. A moderate sized anomaly is found on the southern shore due south of Paoha Island. There, the highest gradients are about $500^{\circ}/\text{km}$. A smaller two station anomaly is located about two miles north of Paoha Island. Stations were made at numerous gas seep areas. Most of these stations had colder than normal thermal gradients, but one station in an anomalous warm gradient area was warm.

The temperature of the bottom water strongly affects the sediment temperature. Where the water is cold the sediment is cooled producing a false positive gradient. Where the water is warm it warms the sediment causing a negative gradient.

A very large area of apparent negative thermal gradient occurs at shallow-water stations principally on the northern and eastern part of the lake. These gradients are produced by seasonal warming of the lake water.

Below the thermocline the temperature-depth relationship follow a regular pattern and most stations fit within about $.3^{\circ}\text{C}$ of a curve plotted through the data. Some stations have anomalously warm temperatures, mostly near hot spring areas or the young volcanic rocks. Near one known hot spring there was a distinct warmer near-bottom layer than extended upward about one meter. Other thermal anomalies occur where wind forces warmed surface water to the eastern side of the lake. In response, colder water upwells on the western shore and as the east side of the islands.

The operation and handling of the probe is simple and can be accomplished by 2 people but other logistical operations require a crew of three.

The probe yielded good precision when operated under field conditions. Accuracy is based on laboratory calibration. The precision was tested at several levels in a heirarchy. The differences between reading a single

thermistor in the water column was about $S^* = .03^\circ$ when differences due to distortion of the water stratification were removed. One thermistor (T3) was occasionally slightly erratic, but it was simple to remove its effects from the data and computations.

In the sediment, the differences between measurements on the same thermistor during different runs was tested to be $S = .06^\circ$. The pooled differences between thermistors within stations at 16 randomly selected stations was about $S = .08^\circ$, but part of this error is attributed to not waiting long enough for equilibration. With proper equilibration procedures, the error would have been about $S = .05^\circ$. The standard deviation of differences in thermal gradient was $S = 65^\circ/\text{Km}$ when the thermal gradient is extrapolated from $^\circ/\text{meter}$ to $^\circ/\text{Kilometer}$.

The natural variability within a station is far greater than instrumental errors. The error of this component at the base station was about $S = .3^\circ$.

The principal limitations of the probe are its inability to penetrate in all but very soft bottom and its durability. The probe failed to penetrate at more than 20 stations where measurements were attempted. The probe was bent when penetration was attempted by use of greater impact velocity. On the Salton Sea, the fiberglass probe was broken attempting to penetrate sand bottom.

CONCLUSIONS

1. The geothermal potential of Mono Lake is rated as fair. There are three areas with geothermal heating. The largest and most promising appearing area trends across the lake through Paoha Island and Negit Island. The highest gradient is near Hot Springs Point, an area that contains nearly boiling springs.

* S = Standard deviation, the square root of the arithmetic mean of the squares of the deviations from the mean of the variates.

$$S = \sqrt{\overline{x^2} - \bar{x}^2}$$

The second largest anomaly is on the southern shore, near Rush Creek. This anomaly was drilled to basement and no geothermal potential found. A third anomaly occurs north of Paoha Island and appears small in area.

More than three-fourths of the area under the lake had very low or negative thermal gradient at the time of the study. The area around Hot Springs Point and the accompanying anomalous trend may represent ten percent of the total area and merits further attention. This geothermal feature is very recent and may be underrepresented at the surface because of the low diffusivity of temperature.

2. The thermal probe designed and constructed by the Lawrence Berkeley Laboratory proved useful for locating thermal anomalies in the lake. The instrument is simple to handle and operate. Instrumental errors are small compared to natural lake bottom variability. One limitation is that equilibration time as long as 20 minutes is required to obtain the best precision.

In soft bottom areas a much longer probe could have been used. On the other hand, the probe failed to penetrate in hard bottom areas which restricted work to deeper water areas.

3. The temperature of the bottom correlates with the temperature of the water, and the bottom is seasonally warmed or cooled by the water. In order to recognize anomalous bottom conditions it may be necessary to define the thermal structure of the lake.

In areas of marked thermal activity, such as near Hot Springs Point, there are thermal anomalies in the water column. These anomalies may be limited in upward extent and are most pronounced next to the bottom.

There are anomalous water temperatures due to distortion of the thermal structure by density waves, surface waves, currents and upwelling. These anomalies are not related to geothermal heating.

4. Logistical problems are significant, even when using a small boat. Navigation problems such as long sights, cause uncertainty in location. Improved confidence can be obtained shore-based observers, but this would greatly increase crew costs. Electronic ranging equipment would greatly improve navigation, but at a great increase in cost. For reconnaissance purposes the methods used for this study appear adequate.

5. It is recommended that future surveys consider these procedures.

- (a) There should be more than one design of probe, a longer probe for soft bottoms and a sturdy heavy probe for hard bottoms. The distance between the bottom and probe should be monitored by a transducer mounted in the weight stand plate.
- (b) The thermal structure of the water column should be measured at a station using an auxiliary thermistor array while the standard probe is equilibrating.
- (c) Between stations a near bottom thermal profile should be made using a thermistor array kept near bottom by a weak link attached weight. The interval between the bottom and thermistor should be determined by a high frequency (50 - 200 khz) transducer.
- (d) A standard calibration test should be worked out, such as ice water, for field testing the probe.

MONO LAKE GEOTHERMAL STUDY

INTRODUCTION

Mono Lake was selected for thermal study because of its known thermal and geologic conditions. Numerous thermal springs are found in the region surrounding the lake and very hot thermal springs occur on Paoha Island in the center of the lake. There is a large sedimentary basin filled with at least 2,000 - 3,000 feet or more of sediments as demonstrated by borings on the margins of the lake (Axtell, 1972) and on Paoha Island (Lajoie, 1968). These sediments are water saturated as demonstrated by the volume of water escaping from springs, many of which are sublacustrine.

There are young volcanic rocks throughout the Mono Basin and very young volcanic rocks on the islands in the lake. The volcanic rocks are intrusive into uplifted lake bottom sediments on Paoha Island. These sediments are dated to be about 3,000 years B.P. (Lajoie, 1968) Christensen and others 1969. Tufa coatings on volcanic rocks suggest that the sequence of young volcanism proceeded from Black Point, through Negit Island to Paoha Island (Mason, 1967).

Location

Mono Lake is located in eastern central California at the base of the Sierra Nevada escarpment, immediately east of Yosemite National Park. The lake is just off highway U. S. 395, roughly half way between Bishop and Lake Tahoe. The middle of the lake lies at 38° N, 119° W.

Physical, Chemical, and Biologic Aspects

It is the third largest lake in the state with an area of 77 square miles in 1964 (Mason, 1967). The lake is semi-elliptical in shape with a long dimension

about fourteen miles and a width of about ten miles but as low as about two and one half miles in the western arm. It is a remnant of the ancient Lake Russell which approximated 800 square miles in area.

The lake is very saline, much more than twice saltier than the ocean, and relative to the chemical proportions of the ocean contains large amounts of sodium, boron, potassium, carbonate and bicarbonate. It is relatively deficient in calcium, magnesium and chlorine. No fish can live in the lake, but it does support a few species of plankton, diatoms, protozoans, rotifers, and a crustacean. These form a food chain that supports amazing numbers of birds that include grebes, gulls, phalaropes and terns.

Weather

The following weather conditions for a station on the west side of Mono Lake for the interval from 1951 to 1964 have been abstracted from Mason (1967, p. 16 - 19):

Mean Annual Temperature $9.1^{\circ}\text{C} \pm (s) 0.4^{\circ}\text{C}$

Mean Annual Precipitation $32.8\text{ cm} \pm 13\text{ cm}$

Mean Annual Wind Speed 402 cm/sec (Lee Vining Ranger Station)

Annual evaporation from lake 95 cm/yr

Water Temp. (surface) 0°C to 20° (Aug.) (The lake water has never been observed to freeze but ice forms locally where fresh water overflows the lake.)

During the period of the study the approximate following conditions prevailed:

Mean Temperature Range $14^{\circ}\text{C} - 16^{\circ}\text{C}$ ($57^{\circ} - 61^{\circ}\text{F}$) at Lee Vining
a trace of precipitation.

Highest water temperature of lake was 17°C .

The mean wind speed about 5 miles per hour.

The morning winds were calm or light and variable on all but two days. Starting about noon, but as early as 10:30 a.m. winds came downslope from the mountains to the west and were strongest near the passes from the southwest in the southern arm and northwest or west in the northern arm. In the eastern part of the lake the afternoon winds were from the southwest. Afternoon winds typically reached about 15 miles per hour but undoubtedly exceeded 25 miles per hour in gusts.

Methods

A base map was prepared by combining parts of four U. S. Geological Survey 15-minute topographic quadrangles that intersect near the center of Mono Lake (Bodie, Mono Craters, Trench Canyon and Cowtrack Mountain) scale 1:62,500. Unfortunately, these maps were made more than a decade apart which has produced marked shoreline discontinuities because of the receding water level. Scholl and others (1867) prepared a map of the lake floor for July, 1964. The lake level has receded about 27 feet since that time.

The first two days at the lake were spent getting access across private property, principally to the only suitable launching site on the lake, near Danburg Beach, and inspecting onshore navigation controls.

The first twelve stations were marked with reference spar buoys that remained anchored at these sites until the end of the study. Each of these was located by several horizontal angle sextant fixes. Other stations were located from these points by dead reckoning courses aided by Brunton compass fixes and sextant angles, but generally with a lesser number of fixes than were made on the original buoys. The errors in navigation weren't checked. It is probable that stations on the west side of the lake, where there were numerous close sights, are good, perhaps

within one-eighth mile. But the eastern part of the lake posed many navigation problems because long sights were required and well known or easily recognizable onshore features to sight on were less available. Reference buoys sometimes required some looking to locate. At times the buoys were easy to locate and could be seen perhaps a mile away. At other times the boat passed within a hundred yards or so of a buoy, yet it wasn't seen. The general case was when it was windy with waves and glare on the water, the buoys could be hard to find, and when it was calm they were easily found. A principal problem with the navigation method used was that it was very time consuming. The station would be approached in jumps by running by time from the previous buoy, stopping, sighting, running, sighting, etc., sometimes back and forth until satisfactory agreement could be obtained. In addition to the sighting errors, the plotting error on the work map was a problem. The three arm plotter could not be set much better than about one-half degree and sometimes as much as a degree between settings might have occurred.

Logistical activities took a considerable part of the field time and effort during the Mono Lake study. There were no launching ramps or boat facilities on the lake. It was necessary to launch and recover the boat from only one site, the rocky beach at Danbury Beach. During the morning the lake was usually calm, so launching the boat became fairly routine but was time consuming. In distinct contrast, recovering the boat was mostly a major problem because the moderate to strong winds and longshore waves made it very difficult to get and keep the boat and trailer aligned while loading. The caustic water has an accumulative effect on the skin and the field crew acquired badly cracked and irritated hands, so getting in and out of the water daily was getting to be a less and less welcome experience. The crew was delighted when Mr. John Crosby, manager of the brine

shrimp harvesting offered use of a new dock he had just installed for the 1976 season. He provided the most convenient spot at the dock and saved five days of launching and recovering the boat.

Once the boat was in the water, it was a simple task to get to the base station and measure there. Then other stations were measured in a semi-random order. This procedure was done so that there wouldn't be a series of stations at one time in one region of the lake, then another series at another region in the next time to avoid the possibility of zoning the lake on a time basis. But we inevitably found the boat well downwind from the landing site whenever the wind came up, and a long wet beat upwind was required at the end of each day.

The procedure at most stations was the same once navigating there was completed. A bow anchor was placed well upwind from the station and line laid out amounting to about four times the water depth as scope on the anchor. After the boat was lying to the wind and all the scope was used, a stern anchor was dropped. About half of the original scope on the bow was recovered and scope layed out on the stern. Then the corer was dropped off the bow and when on bottom was spudded slightly to achieve maximum penetration. The lines were readjusted with more scope on the bow and line recovered on the stern. The corer weighs 26 pounds, and when it penetrates with a three foot barrel, it is a formidable anchor. The corer was left on bottom until the probe was recovered unless there was some concern about the bottom being hard. Then the corer was usually returned to the bottom with a dummy barrel.

With the aid of the davit and handles on the electric cable reel, it was no problem to put out or recover the probe, even in water depths of 130 feet. But, recovering the corer and bow anchor at the over 6,000 feet elevation of

the lake left the crew huffing and puffing.

It was never certain how far the probe penetrated. The weights were usually covered with mud, but not the wider plate above the weights which suggests that the lower thermistor was 135 cm in the sediment. There were 20 cm intervals between T1 and T5, so the interval measured was mostly between 135 and 55 cm below the lake bottom. Occasionally the weights had very little evidence of sediment when the probe was sloshed around on the surface to clean it for the next station, but the temperature of T-5 showed it was in the sediment. This suggests that the probe penetrated to the base of the weights, and penetration was about 120 cm with the thermistors between 120 and 40 cm.

SAMPLING STATIONS

On the base map the area of the lake is about 77 square miles, but subsequent to the time maps were prepared, the area has diminished because of the receding water level. In order to anticipate covering the entire lake with near uniform coverage, it was necessary to have relatively large spacing between stations. Based on the previous sampling at Salton Sea it was estimated that it would require approximately one hour per station to make measurements and between station transits. It was planned to make daily measurements at one and perhaps more base stations. Thus it was anticipated that no more than six or seven stations per day net would be sampled. If the weather and other operating conditions were favorable, about 80 stations could be measured during the period allotted to the field study of this lake. Therefore, a one-mile interval grid of stations was set up over the lake. Because of the scale of the base map, this was simply a one-inch grid over the map, and the section lines on the topographic maps proved to be handy interval references.

There were 78 original grid points plotted on the base map of the lake, but when the study was in progress 23 of these proved to be inaccessible due to shallow water, or the probe did not completely penetrate the bottom. At four stations where the probe would not penetrate, water measurements were made. There were twelve additional stations where probe measurements were made at locations of special interest, such as gas seeps or near hot springs. Figure 1 shows the location of the stations measured. Some stations represent several probe measurement points such as the base station or where traverses of probe lowerings and temperature measurements were made to some feature of interest.

Temperature measurements were made at about 80 locations during the 13 days spent on Mono Lake. Success in obtaining measurements below the lake bottom was largely related to the type of bottom encountered, which in turn related to the water depth. Very shallow areas are usually rock, gravel, or sand, while areas below about 30 feet were usually soft mud. Between about 20 and 30 feet the bottom is mixed and penetration is uncertain, occasionally successful, frequently not. In those parts of the lake where the bottom is soft, the probe penetrated to the weight stand, and temperature measurements were obtained at 20 cm intervals to one meter depth and from the water immediately above bottom. None of the temperatures were particularly warm and they are distinctly nonuniform. The bottom temperatures ranged from 4.5°C to 15.2° , with the coldest temperature southwest of Paoha Island beneath the deep water (>100 ft.) of the Johnson Basin while the warmer temperatures were associated with the shallow-water areas of the northern part of the lake east of Black Point.

In most cases the temperature of the bottom sediment is very similar to the temperature of the overlying water. In order to recognize anomalously warm bottom temperatures or anomalies in the water column, it appears necessary to develop a suitable temperature model for the lake as a whole.

FIGURE 1

0 1 2 3 4 5 MILES
SCALE

BOTTOM WATER TEMPERATURES

At stations where the probe penetrated the bottom, water temperatures immediately above bottom were measured by the water thermistor. Such measurements were available from about 70 stations. These measurements have the benefit of having been made by a single thermistor and any between-thermistor calibration effects were avoided.

The depth at each station was measured by a sounding line. Depths may be in error on the deep side for two reasons: (1) They were frequently taken before anchoring the boat and if the boat was drifting, the line may not have been vertical. (2) The weight may have penetrated considerable very soft sediment before the bottom was detected by the leadsman.

Figure 2 shows the relationship between bottom water temperature and depth. The temperature ranges from 4.8° to 15.5° C. over a depth range of from 130 feet to 11 feet below the water surface. The water temperature increases only about one and one-half degrees between 130 feet and 40 feet; then the temperature gradient increases markedly to the shallowest station on the lake at 11 feet. This marked change in thermal gradient over a small depth interval is the thermocline. The thermocline is a zone of density stratification and subject to rapid changes in position due to density waves. However, the water below the thermocline has small uniform temperature changes over a great depth range. As an average, the base of the thermocline is about 38 feet deep. The base of the thermocline appears depressed on the eastern side of the lake because the prevailing wind drives the warmed surface water to that region. The compensating water movement is an upwelling along the western shore that elevates the thermocline and produces colder than average temperatures in that region.

FIGURE 2. T_w °C WITH PROBE IN SEDIMENT

The curve shown on Figure 2, hereinafter known as curve A, is an estimation of the normal thermal gradient for the lower and middle part of the water column during the study period. Most stations have temperature-depth relationships that plot within $.3^{\circ}$ of the curve. This approximates the temperature range at the base station during the study period. Some plots are significantly further to the right of curve A than this range. These stations appear to be anomalously warm, and they are bounded into separate fields on the figure. When these stations are located on the map, they group into two areas. Many are areally associated with the very young volcanic rocks and known hot springs of the islands. The second grouping is along the southeastern shoreline where the anomalously warm water is attributed to distortion of the thermal structure by the massing of wind-forced surface water in that region. All but one of these stations near the southeast shoreline have sediment temperatures that are lower than the water temperature.

WATER COLUMN TEMPERATURE

At many stations where the bottom was firm and the probe wouldn't penetrate, temperature measurements were made in the water column. In addition, at numerous locations, temperature measurements were made at several intervals in the water column. Water temperatures were measured in areas near known hot springs or gas seeps to test the extent of their influence on the water column.

Figure 3 shows the plotting of water column measurements. These measurements show the range of temperatures determined by all thermistors on the probe and the arithmetic mean of the six readings. These data are compared with curve A (dashed line) from bottom water (TW) stations determined for Figure 2. Mean temperatures of stations that are not in the vicinity of hot springs fit the bottom water curve well. There is, however, considerable scatter between

FIGURE 3.

thermistors at each probe station. Scatter results when all probe readings at a given depth are compared. For example, six probe stations had measurements at 50 feet. The range of temperatures determined for these stations was about 5.8° to 6.8° C. Two stations, 69 and 70, representing a hot spring area, can be eliminated from this discussion. The range of the remaining thermistor readings at this depth is somewhat greater than would be expected. These and data from other stations shown in Figure 4 suggest that there were between-thermistor or calibration errors that would affect the determination of the thermal gradient. Figure 4 (lower) was obtained at Station 64. The probe was read near bottom and raised in short increments to near the surface. At nearly the same depth different thermistors were read on successive raisings. If each thermistor were accurately calibrated and the precision error minimal, all thermistors would be expected to read the same temperature at a common depth, and the same curve would be obtained when points were connected. However, in Figure 4, both Stations 64 and 62 A-G show broadish bands of lines. The widest departure from a line through the center of the band is produced by T3, and this thermistor demonstrates the most between-measurement scatter within the family of curves. When the 200-foot electrical cable, required for the deeper water of Mono Lake, was attached and the instrument checked out, T-3 was a matter of concern as the voltage reading differed from the other thermistors. The use of this thermistor adds little to the interpretation of the data. In fact, the use of only three thermistors simplifies analyzing the data. The water temperature (T_w) is required as a baseline measurement. The bottom thermistor (T-1) provides the maximum penetration. The greatest interval in the sediment (80 cm)

FIGURE 4. WATER COLUMN TEMPERATURE.

is provided by using T-1 and T-5. Figure 4 suggests that a reliable temperature may be obtained from T-5. TW and T-1 will demonstrate if a station is anomalously warm, while T-5 and T-1 provide the thermal gradient.

WITHIN STATION MEASUREMENTS

It was planned to monitor frequently for possible changes in water column temperatures or the probe, because of some mechanical failure. One would not expect any sudden great change in sediment temperature one meter below the bottom and repeated measurements would provide a continuing reference. The original plan was to make daily temperature measurements at a base station. This was accomplished on 11 of 13 days when water column and lake bottom measurements were made at station 1. The results of these measurements are shown in Figure 5. Strong afternoon winds on May 19 and 21 precluded making planned afternoon measurements on those days. All of the measurements were made in the immediate vicinity of a well anchored buoy. The anchoring procedure and making sure the buoy wasn't fouled, made it difficult to exactly predict the final position of the boat. Measurements were made all around the buoy probably within an area of about 10,000 square feet.

During the study period the base station water temperature at the lake bottom as determined by the water thermistor (Tw) ranged from 5.29°C to 5.63°C or a range of $.34^{\circ}\text{C}$ over the 13-day period. There is an apparent uniform gradient increasing from 5.35°C to 5.47°C shown by 8 of the 11 measurements. The dispersion of these measurements from the gradient line is no more than $S = .03^{\circ}\text{C}$. On the other three days, the water temperatures deviated from the gradient line as much as $.18^{\circ}\text{C}$, but these changes were not accompanied by any significant temperature changes in sediment temperature. Erratic water column temperatures have been described by Mason (1967, pp. 19-20) who presumed them

FIGURE 5. REPEATED MEASUREMENTS AT ONE STATION (STATION 1)

to result from internal seiche distortions of the water stratification.

Other stations provide data to estimate the precision error in the water column. Stations 62 A-H form a traverse between the northern shore and Negit Island. This traverse was made attempting to find locations where bottom penetration could be achieved in the northern area of the lake. Failing to accomplish this, a series of water temperature stations were measured. These data are shown on Figure 6. At each station the temperature-depth relationships appear isothermal over the length of the probe. Between stations, however, the temperatures increase as the water depth decreases. Thermistor 3 is considered erratic and has been eliminated from this discussion. When T3 and thermistors in the sediment are eliminated there are very little differences between temperatures at a given station. The differences between individual temperatures and fitted curves through each set of data suggest that the precision error is about $.05^{\circ}\text{C}$. This is comparable to the water column data at the base station.

Sediment temperatures at one meter below the lake bottom, measured by T1 and shown on Figure 5, ranged from 4.85° to 5.27° during the 11 days of measurements. The temperature distribution appears distinctly bimodal, with one mode about 4.94° and the other mode at about 5.22° . The dispersion about either of these modes is approximately $S = .05^{\circ}\text{C}$.

Instructions for the use of the probe indicate that the operators should wait 10 to 15 minutes after lowering the probe into the bottom to allow for the probe/bottom temperature, that has been frictionally heated by impact, to equilibrate. Figure 7 shows the gradual drop in temperature readings for thermistor 2 between 3 and 15 minutes after probe was in bottom. It can be noted that the temperature reading dropped 0.64°C during this short time interval and the temperature drop between 10 and 15 minutes about 0.1°C .

FIGURE 6. WATER TEMPERATURES VS. DEPTH.

In practice the crew would wait until 10 minutes had elapsed from the on bottom time for the probe to equilibrate, as the instructions indicate. Then the on deck instruments were set up and plugged in, a procedure taking about two to three minutes, and the reading sequence commenced. Therefore, a typical reading sequence in the low power mode took place between about 13 and 18 minutes after the probe was in the bottom.

Figure 7 suggests that equilibration was continuing over this period and produced an estimated within station temperature difference at one thermistor of about $.06^{\circ}\text{C}$, which appears to be the most significant within station instrument error component and is consisted with the estimate of $S = .05^{\circ}\text{C}$ for Thermistor 1 shown above. This error appears to actually be procedural rather than instrumental. It is a small component, however, of the errors at a given station.

It is concluded that the within location (within 10,000 sq. feet) temperature variability at the base station significantly exceeds the instrumental errors, with the location variability about 0.3°C . In addition, it is assumed that all locations within the lake potentially have this amount of variability. However, it is to be noted that measurements of numerous adjacent stations with similar depths showed differences not much greater than the instrumental error determined at the base station. For example, Stations 4, 23, 27, 51, 52, 53, located in deep water south of Paoha Island represent an area of about six square miles. The sediment temperatures at one meter (T1) differ little more than would be expected from the level of instrument error described for the base station.

FIGURE 7. CHANGE IN TEMPERATURE OF THERMISTOR 2 DURING EQUILIBRATION

In contrast, other adjacent stations with similar water depth may differ considerably such as Stations 6 and 33, less than one-half mile apart differ in sediment temperature by one-half degree.

BOTTOM MEASUREMENTS

Figure 8 shows stations where probe measurements were made. The data plotted include: water depth, bottom water temperature, sediment temperature at about one meter, and the difference between water temperature and sediment temperature. The water temperature was taken as the standard and individual station readings were compared with Figure 2 to determine how closely they fit the curve. As a method of assessing the essential temperature characteristics of the lake bottom and to recognize anomalies, the temperature of the bottom water (TW) was subtracted from the temperature of the sediment at about one meter (T₁₃₅ Cm). Negative readings indicate that the water temperatures exceed the sediment temperature, while positive readings show that the sediment is warmer than the water. As a model, it was assumed that the bottom temperature would be the same as the sediment temperature. The actual data show that the water is warmer than the sediment most of the time. These data have been summarized in histogram form in Figure 9.

Most of the data form a discrete normal distribution with a mode between $-.2^{\circ}$ and $-.4^{\circ}$ C. The arithmetic mean of the distribution is $-.23$ and the standard deviation is $.33$. Therefore, all stations with differences between $+.4^{\circ}$ and $-.9^{\circ}$ are very likely within this distribution. Other stations slightly more dispersed from the mean may also be part of the principal population.

Obviously distinct from this population are several stations where the sediment temperatures are much less than that of the overlying water. The surface

FIGURE 8

FIGURE 9. STATIONS HAVING DIFFERENCES $T_i - T_w$

water is being strongly influenced by solar heating and in shallow water areas the surface sediment is warmed by the water. Hence, sediment temperatures decrease from the bottom to one meter. Stations 36 and 60 are examples of this distribution as shown in Table 1.

Table 1

Thermistor Temperature in Degrees Celsius (°C)

	<u>#36 - Depth 25 Feet</u>	<u>#60 - Depth 17 Feet</u>
Tw	12.4°	14.4°
T5	9.1°	12.8°
T4	8.5°	12.1°
T3	8.2°	11.5°
T2	8.0°	10.8°
T1	8.0°	10.6°

Equally distinct and of principal interest to this project are those stations where the sediment is warmer than normal. Stations 64 and 70 are examples of this characteristic where the sediment is more than 2° C. warmer than the water. The probe readings at these stations are:

Table 2

<u>Station 64 - Depth 49 Feet</u>		<u>Station 70 - Depth 116 Feet</u>
<u>Thermistor</u>	<u>Temperature</u>	<u>Temperature</u>
Tw	5.9°	5.3°
T5	7.3°	6.2°
T4	7.6°	6.5°
T3	7.8°	6.8°
T2	8.1°	7.2°
T1	8.5°	7.7°
Thermal Gradient T1-T5	1764°/Km	1905°/Km

It can be noted that in the bottom-sediment, the temperature gradients of these stations are similar, but the gradient between T_5 and T_w is much greater for Station 64 than for Station 70. When the water temperatures of these stations are compared with the curve shown on Figure 2, it can be seen that Station 70 is about $.3^\circ$ warmer than the curve while Station 64 is about $.1^\circ$ colder. If these stations had water temperatures of the curve, they would have very similar thermal gradients. It is probable that the water near Station 70 has been warmed by geothermal heating, but at Station 64, which is very near hot springs, the bottom water (at least at the time of measurement) is more affected by the upwelling of deeper water from the Putnam Basin.

THERMAL GRADIENTS

Figure 10 is a histogram of the thermal gradient between T_1 and T_5 extrapolated to degrees per kilometer with positive gradients for sediment becoming warmer with depth. The histogram is unimodal with the mode near zero degrees per kilometer thermal gradient. More than 60% of the stations are between plus and minus 200° per kilometer or very low gradient. About 15% of the stations have slight positive gradients while 5% have slight negative gradient. The seasonal heating strongly affected about 10% of the stations. Moderate to strong positive thermal gradients occur at about 10% of the stations.

There is uncertainty about thermal gradient values due to within station differences. The gradients determined at the base station differed from day to day but show no obvious trend. The standard deviation of the differences is $S=65^\circ/\text{km}$, and it is assumed that all locations potentially differ that much. Therefore, discrimination between stations with differences less than $100^\circ/\text{km}$ cannot be made confidently but differences greater than $200^\circ/\text{km}$ can be.

FIGURE 10. THERMAL GRADIENT T₁-T₅ (80 cm)

As was shown in Figure 10 most of the gradients measured range between plus and minus $200^{\circ}/\text{km}$. This accounts for more than 60 percent of the stations measured, and this gradient is ordinarily of no great significance to this study.

There are three areas with anomalous positive thermal gradients. The largest area and containing the stations with the highest gradients is a narrow zone extending northwestward across the lake from the southern shore to Negit Island. This zone is about centered on Hot Springs Point on Paoha Island. No probe penetration could be achieved in the very shallow water north of Negit Island, but the zone trends toward that area and directly at the hot spring on Black Point. Over much of the zone, the high gradients appear related to the young volcanic rocks. The sequence of volcanic rocks decreases in age from Black Point to Negit Island to Paoha Island. The temperature gradients appear to follow this sequence. The highest gradients range from about $1000^{\circ}/\text{km}$ to $2000^{\circ}/\text{km}$ near Hot Springs Point and diminish away from there. The gradient on the north side of Paoha Island and off Negit Island is about $400^{\circ}/\text{km}$.

A moderate-sized anomaly is found on the southern shore due south of Paoha Island. The highest gradients are about $500^{\circ}/\text{km}$. A smaller two station anomaly is located about two miles north of Paoha Island.

When Figure 8 is inspected and the bottom water temperatures considered, with respect to the curve of Figure 2, most of the stations measured near the volcanic rocks of Paoha Island appear anomalously warm. For example, Station 65, located north of Paoha Island, has a $-.49^{\circ}$ difference between sediment at about one meter and the water temperature. This places the thermal characteristics of this station marginally to that of the normal population for the lake as a whole, and it can't be resolved from that population solely on the basis of that data. But, the water at Station 65 is more than $.4^{\circ}$ warmer than the normal position of curve A. When the water temperature is considered, this station is well

beyond the normal population and therefore should be considered thermally anomalous. Other stations where sediment temperatures at about one meter are higher than water temperatures are 19, 16, 3, 18, and 8. The first two of these stations have water temperatures warmer than curve A, while the next two are about on the normal curve, but the water temperature at Station 8 is colder than curve A for that depth. The probe temperature readings for these stations are shown in Table 3.

Table 3

Temperatures, (°C) at Five Mono Lake Stations

<u>Stations</u>	<u>19(depth 38')</u>	<u>16(depth 45')</u>	<u>3(depth 81')</u>	<u>18(depth 41')</u>	<u>8(depth 39')</u>
<u>Thermistors</u>					
Tw	6.98°	6.49°	5.41°	6.48°	6.16°
T5	6.90°	6.60°	5.29°	7.11°	6.78°
T4	6.94°	6.64°	5.35°	7.00°	6.80°
T3	7.02	6.73°	5.48°	7.00°	6.66°
T2	7.15°	6.77°	5.53°	6.85°	6.51°
T1	<u>7.18°</u>	<u>6.93°</u>	<u>5.71°</u>	<u>6.99°</u>	<u>6.57°</u>
Thermal Gradient T1-T5	328°/Km	371°/Km	416°/Km	-119°/Km	-215°/Km

It can be seen in Table 3 that Stations 19, 16, and 3 have moderately increasing temperatures with depth which projected over a depth of one kilometer exceed 300° per kilometer. While these gradients are markedly less than shown in Table 2, these stations are still of geothermal interest. Station 19 is in a cove off Negit Island and is in close proximity to the young volcanics of the island. Station 16 is more than one mile from exposed young volcanic rocks.

Its thermal characteristics are very similar to Station 19. The water temperature plots about 25° warmer than the curve A.

Station 3 is located on the southwestern shoreline near the mouth of Rush Creek. The presence of the creek could subject this location to more than average water temperature variations, but no stream flow was evident, and the bottom water temperature plots vary near curve A. The thermal gradient of this station extrapolates to over 400° per kilometer. This station is relatively close to a geothermal test well. Geothermal Resources International, Inc. "State PRC 4397.1", was directionally drilled 4110 feet to granite basement and from the southern shore to slightly under the lake (Axtell, 1972). The well recorded a highest temperature of only about 130° F, and the well demonstrated a thermal gradient less than normal. None of the very young volcanic rocks similar to those found on the islands were encountered in the well. A planned station was located in the immediate vicinity of the geothermal well, but the location was in a maze of tufa towers, and the bottom was not penetrated by the probe.

As shown in Table 3, despite the sediment being warmer than the water, stations 8 and 18 have negative gradients between T1 and T5. The water temperature at station 8 plots about .25° colder than curve A. This station is in an area of abundant gas seeps which may cause an upwelling effect that brings in colder bottom water from the adjacent Johnson Basin.

There are other stations of geothermal interest in the lake. Most are located near Paoha Island. At stations 11, 54, and 50 sediment temperatures become warmer with depth and show thermal gradients equivalent to between 100° to 400°/Km.

These data suggest that the island is the most active geothermal area in the lake and the area of geothermal heating may extend under the lake for several miles. In this respect station 13 is of interest. Although the temperature of the sediment is less than the water temperature, the bottom water is far warmer than would be expected based on curve A. Within the sediment temperatures at station 13 increase somewhat with depth producing a thermal gradient that extrapolates to $172^{\circ}/\text{Km}$. This extends previously described data from Negit Island to the southern shore. The thermally active zone ranges in gradient from $146^{\circ}/\text{Km}$ to $1900^{\circ}/\text{Km}$ and is probably narrow but the boundaries are not accurately determined. It includes Hot Springs Point on Paoha Island and the highest gradient measured was at station 70. The zone is bounded by stations with negative or low thermal gradients. This and other thermally active areas are shown on Figure 8. A small area including stations 16 and 37 had moderate gradients ranging from $197^{\circ}/\text{Km}$ to $371^{\circ}/\text{Km}$ (#16).

GAS SEEPS

Measurements were made at many of the larger gas seeps. They registered both positive and negative gradients, but for the most part they appear to have anomalously negative gradients. The only large seep with a pronounced positive gradient is at station 50 where the gradient is about $+300^{\circ}/\text{Km}$. Station 20 is a large seep area less than one-half mile from the base station. It has a gradient of almost $-300^{\circ}/\text{Km}$ while the average for the base was about $+200^{\circ}/\text{Km}$. Stations 5 and 40 are less than one-half mile apart and have the same water depth of 105 feet. Station 40 is on a large seep with a thermal gradient of almost $-200^{\circ}/\text{km}$ while station 5 has a positive gradient.

Stations with very strong apparent negative gradients are located in the

northern and eastern part of the lake where the lake is shallow seasonal heating is affecting the sediment as well as the lake water. The steepest gradient projects to almost $-4000^{\circ}/\text{Km}$ at station 61 in 13 feet of water. Nearby station 60 calculates at almost $-3000^{\circ}/\text{Km}$, while the adjacent station 36 in water 25 feet deep read about $-1500^{\circ}/\text{Km}$.

No stations with depths of 50 feet or more seemed to be affected at the time of the study by the effect of seasonal heating. But shallow stations are interpretive problems. Station 63 is a case in point. Its gradient calculates at $-43^{\circ}/\text{Km}$ and shouldn't be of great interest, but is next to Negit Island where positive readings might be expected. This station is only in 11 feet of water where a gradient of $-4000^{\circ}/\text{Km}$ might be expected. Without the seasonal thermal effect this station could have a strongly positive gradient.

It appears that a much longer probe is necessary to assess these stations. It should be noted, however, that penetration was a consistent problem in shallow water areas on Mono Lake, and a longer probe may not have penetrated in these areas.

DISCUSSION ON SEASONAL EFFECTS

One of the principal problems in evaluating geothermal data from the study of the shallow probe measurements is the problem of resolving between thermal gradients produced by geothermal heating and thermal gradients produced by solar heating. In one case the solar effects may be so intense that it apparently overpowers any geothermal effects. In another case previously induced solar heating (pseudo geothermal heating) appears to produce geothermal heating at the time when solar heating is lowest. The third case is where the rate of change of water temperature is greatest and apparent, anomalies result

because all stations can't be measured at exactly the same time. It was hoped that computer modeling would resolve the problem, but presently the problem appears far from solved. This is not to suggest that computer modeling is not exceedingly worthwhile. The problem is that more and better data appear necessary.

According to studies of the water temperature of the lake by Mason in 1964, the annual thermal wave is irregular and appears to depart considerably from a sine wave form. The maximum depth reached by different isotherms occurred at markedly different times during the year. For example, the 20° C isotherm reached 10 meters in depth during mid-August, but at 20 meters the temperature was only 7° C. The 10° C isotherm first reached 20 meters in early September, but extended to its greatest depth, over 25 meters in early November. Different levels of the lake reached their maximum temperature at different times under the heating cycle. In marked contrast, the cooling cycle was one of very rapid change with the temperature of the entire lake (to a depth of 25 meters) dropping from about 11.5° C to 6.5° C in about one-half month. In a general sense the thermal gradient is most negative when the water is warmest and most positive when the water is coldest. But, if the highs occur in different parts of the lake at different times, the lake becomes zoned with different thermal gradients in each area according to depth.

It appears that measurements made following a period when the lake has been nearly isothermal for an extensive time interval (in Mono Lake during the cooling period) will provide the best opportunity to define anomalous thermal areas, but not necessarily the true thermal gradient.

Another solution is to make repetitive measurements at sites of interest or to make measurements from the same stations over a long time duration. But none of these alternatives fit into the present study.

EXTENT OF WATER COLUMN HEATING

Tests were made of the effect and extent of geothermal heating on the water column. The purpose of these tests was to evaluate the feasibility and procedures required to locate lake bottom thermal anomalies from water column measurements which relate, in part, to continuing evaluation of geothermal exploration methods such as those submitted to the State Lands Commission in the initial phase of this project in response to requests for proposals. Particular proposals were rejected because adequate data were not available to evaluate procedures for obtaining or making practical interpretation of such data. The water column was recognized as highly dynamic and subject to peculiar-appearing phenomena, some of which were observed during this study.

Several tests were made near Paoha Island where a number of hot springs trickle from cracks in the volcanic rocks and under the gravel beach. The beach is frequently warm or hot to touch, and where pools form, temperatures ranging from about 70°C to over 80° C were measured. The highest temperature observed was 97° directly from a hot spring on the west side of the point. Figure 12 shows a series of measurements made off the gravel beach east of the point in water between 32 and 33 feet deep. Figure 12 shows that the near bottom water is anomalously warm. The water temperature descends only slightly between 15 and 25 feet, then drops about 6° in the next four feet. The temperature reaches a minimum between 29 and 30 feet, but reverses sharply at that point and rises at least 4° until the bottom thermistor, and probably reaches

FIGURE 12. WATER COLUMN TEMPERATURE NEAR
HOT SPRINGS POINT, PAOHA ISLAND.

as high as 12° C or 5° above the minimum temperature over an interval of only about two and one-half feet. This and similar tests in the same area demonstrated a distinct thermally elevated zone that is very restricted in thickness. This thermal zone was not found more than about one meter above bottom. The warmed bottom water is obviously in density imbalance, and upward flow must occur nearby, but wasn't detected in the data collected.

It was previously noted that anomalous water temperatures were detected by the water thermistor when compared with curve A. Only part of the water thermal anomaly relates to geothermal heating. Most of it was produced by solar heating. Only one thermistor in the water column does not allow discrimination between geothermal and solar warming. However, a train of water thermistors or the probe measured just off bottom could show if the heating increases toward bottom (geothermal) or diminishes downward or is isothermal (solar heating). It appears useful to future study to make reconnaissance measurements both in the water column and in the sediment.

ACKNOWLEDGMENTS

The study was made with the assistance of G. C. Crow, D. L. Hoagland, J. W. Barth. B. N. Whiteside helped with field operations and communication. Logistical support was made by N. E. Welday. Pat Kelly kindly granted permission to cross his property to launch the boat. John Crosby granted use of his dock on the lake. K. R. Lajoie provided a list of studies made in the Mono Basin. J. C. Oldson computed all field data and provided a mathematical model study of the seasonal other effects. He delivered and tested the equipment. P. Wilde provided a calibrator curve, tested equipment, and accompanied the field party on two-days. K. Larson drafted all Figures. the manuscript was typed by B. I. Freeman. Financial assistance was provided by the Federal Energy Administration.

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**Thermal Probe Study
of
Salton Sea, California**

by

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SUMMARY

Thermal probe measurements were made in the Salton Sea during mid March, 1976 using an approximately one meter fiberglass probe equipped with 5 internally mounted thermistors and one thermistor in the water.

During the 13 day study, measurements were made at 56 locations in 38 stations with 7 replicate measurements at a base station. During the study two and one-half days were lost to very windy weather and two days to equipment problems. Under favorable conditions 6 or 7 stations per day were measured. Logistical operations required about half of the time.

Temperatures were measured both in the sediment and in the water column. Temperatures ranged from a high of 47.37°C at about one meter in the sediments very near a hot spring in the lake to a low of 14.41°C in the water column near the deepest part of the lake.

The mean temperatures for Probe 1 stations range from 17.58°C at about one meter in the sediment to 15.51°C for the bottom water. These temperatures deviate only a few tenths of a degree from temperatures predicted by a mathematical model based on seasonal variations due to solar heating.

Stations with temperatures warmer than the average and the model are clustered in three areas. There is an 8 station anomaly with an apparent area of over 20 square miles in the southeastern part of the lake. This area could extend westward into the southwestern part of the lake where no measurements were made. There is an anomaly in the northcentral part of the lake with one very anomalous and possibly four somewhat anomalous stations. With considerable uncertainty because of mechanical problems with the probe, there may be a three station anomaly in the mid-central part of the lake. These three anomalous areas suggest a northwestward trending zone of geothermal anomalies extending, probably discontinuously, from the southeast

to the northwest part of the lake.

The probe designed for this study was found to be simple to use and was easily handled. It proved to be too frail for the conditions that it was subjected to. The first probe was broken on a hard bottom station, and the second probe became increasingly erratic during its period of use. (Design changes subsequent to this study have improved these characteristics).

The probe did not penetrate uniformly. In soft bottom it penetrated over one meter. In hard bottom, it did not penetrate. In bottoms of varying firmness, penetration was uncertain. Failure to penetrate produces apparently much lower temperatures than actually exist for a station.

For this study, direct temperature measurements were not available in the field but required elaborate calculations to determine. (Subsequent changes in procedure have made it possible to obtain temperatures in the field).

The probe requires long temperature equilibration times, perhaps 20 minutes, before measurements should begin.

Many of the problems encountered while working on the Salton Sea were related to the weather. The lake is subject to sudden intense winds and equally sudden changes in wind direction. These conditions require multiple anchors at every station. When there is no wind, the visibility is sometimes very poor, such that no shoreline is visible from mid-lake.

Navigation was by horizontal angle sextant measurements, resection by Brunton compass, and dead-reckoning. There was uncertainty in location plotting using a plastic three arm plotter of about one-half degree for each outer arm. Other than visibility the principal navigation problem was the obsolete nature of the base maps where much of the shoreline and near lake features were not shown.

RECOMMENDATIONS

Additional reconnaissance geothermal investigations appear to be warranted in the Salton Sea.

- Several probes of varying length, including probes of two or more meters, should be available.
- Each probe should be equipped with some means of accurately determining the penetration into the sediment.
- Some means of knowing the probe-bottom relationship from the boat should be provided.
- Direct temperature measurements should be available.
- Equilibration times of the order of one-half hour should be used to minimize uncertainty from this source.
- It may be desirable to implant several thermistor arrays as deeply as convenient and monitor them periodically.
- Design considerations should be given to developing some type of probe to penetrate sandy or other firm bottom conditions.

THERMAL PROBE STUDY OF THE SALTON SEA

INTRODUCTION

The purpose of this study was to field test a newly developed thermal probe and to make a preliminary assessment of the geothermal potential of State-owned lands beneath the Salton Sea. The State of California owns mineral rights to four areas of land beneath the Salton Sea and operates the Salton Sea Recreation Area which occupies much of the northeastern part of the lake and the adjacent upland area. The tracts with mineral rights held by the State are shown on Figure 1.

The Salton Sea was selected for thermal probe studies because of its immediate proximity to well known and partially tested geothermal areas and because geophysical data suggest that the geothermal anomalies extend north from the known high thermal gradient area near Obsidian Butte to Red Island and Mullet Island under the southern part of the Salton Sea. Such an area promised to be a most suitable test site.

Location

The Salton Sea is located northwest of El Centro, southeast of Palm Springs and about 90 to 100 miles northeast of San Diego. It is a body of saline water 36 miles long and up to 16 miles wide with an area approximating 360 square miles. It is the largest inland lake in the State.

The water of the Salton Sea has approximately the same salinity as the ocean, but the water is non-marine. The salinity was produced by evaporation of Colorado River and local fresh water runoff and by the lake dissolving salt from its lake bed. The lake occupies the bed of the ancient Lake Cahuilla a fresh water lake many times the size of the present Salton Sea. The salt pan remnant of the ancient

FIGURE 1.

LEGEND

CALIFORNIA
STATE OWNED
LAND.

STATION NUMBER
WATER DEPTH IN FEET

Salton
Sea

lake was a major source of salt for the present lake. The present salinity is about 38% and is increasing annually.

Bottom Topography

The bottom topography was defined by Arnal (1957). The deepest part of the Salton Sea is nearly the lowest elevation in the United States. With respect to sea level, the elevation of the deepest part is about -277 feet, or only four feet higher than Badwater in Death Valley. The deepest water at a sampling station was 48 feet at stations 35 and 36. Subsequent to this study the water level has risen over one foot. The water depths are very similar over much of the central part of the lake. It becomes much shallower in the southern part.

Formation of the Salton Sea

The Salton Sea was formed during 1905-1907 by a flood through a diversion in the Colorado River. Recently irrigation runoff has added to the size of the lake, and the rising water level is presently threatening the resort towns and camps that border the lake.

Uses of the Salton Sea and Biologic Aspects

The lake is a popular recreation area and sportfishing is seasonally excellent with thousands of fishermen enjoying the pastime. Orangethroat corvina, gulf croaker, and sargo are the most popular gamefish, particularly the corvina. The Salton Sea can sustain a corvina population of several million.

The lake and its marginal areas are major wintering areas for migrating birds, particularly ducks and geese. Marsh, wading, and other water birds are very abundant on the lake margins. The State and Federal governments maintain large wildlife refuges in the southern part of the lake. As many as 50,000 geese and 200,000 ducks have been observed in these refuges at a single time.

A very major present problem is the increasing salinity of the lake. If the trend of increasing salinity continues, it will pose a serious threat to the fish and wildlife.

Numerous marinas are found on the northern half of the lake particularly on the western side. There are, however, several nearshore areas with navigation hazards, particularly in the southern part of the Salton Sea.

This study was entirely worked from Bombay Beach on the central eastern shore where the lake widens. Bombay Beach has a marina with easy access, protected wharfs, and available fuel.

Climate

The Salton Sea is located in the western part of the Colorado Desert physiographic province. If it were not for the lake and the abundant irrigation in the adjacent Coachella and Imperial Valley, the region would closely approach the typical desert environment. The annual rainfall is about three inches and the temperature exceeds 100° F for more than 100 days a year. Evaporation greatly exceeds precipitation. Because of the irrigation and the large size of the Salton Sea, the relative humidity is much higher than would be typical for a desert area. The extreme temperatures for the Salton Sea water are a high of 35.3°C and a low of 10°C. The wind at the northern end of the Salton Sea is mostly from the northwest while the wind at the southern end is mostly southwest. This produces a counter clockwise current gyre. The wind and waves can be a major problem when working in the lake. Wind velocities less than 15 knots occur about 90 percent of the time and winds exceed 15 knots 10% of the time. Much of the interval of stronger winds occurs about the time of this study.

Methods

A base map of the entire Salton Sea was available from previous State Lands Division studies. Many distinctive features shown on the 14 U.S.G.S. topographic 7.5 minute quadrangles that contain the Salton Sea were plotted on the existing base map. This map was reduced to a convenient scale and a grid of stations plotted with a spacing of about 2 nautical miles. With this spacing it appeared that the lake would contain about 60 grid point stations. In addition, more detailed sampling was planned for two larger parcels of State land using one-eighth mile spacing and daily measurements were planned at one station. This would provide a hierarchy for estimating sampling errors and location variability. Because of problems of insufficient time, equipment, and bad weather, this sampling scheme was not completed. However, 16 stations were measured within one-quarter section of State land and the base station was measured seven times during 11 days of field measurements.

The base station (station 3) was initially located by transit bearings from several railroad bench marks and a buoy was anchored on the station for reference. All subsequent stations were located by sextant and Brunton compass bearings. The original buoy at station 3 was thought to be lost after 3-2 was measured and another buoy located at the base by sextant bearings. Eventually the original buoy was located about one-eighth mile from the second which gives some indication of the location errors.

Navigation

Navigation to a station was by dead reckoning until the boat was near the proposed location. Then a series of Brunton compass bearings and horizontal angle sextant measurements were made. In addition to the normal problems associated with taking bearings from a small boat, finding suitable, close, well-located features to sight on was a problem as well as the prevailing visibility.

The volcanic buttes near the southern margin of the lake which include Obsidian Butte, Rock Hill, Alamo-Red Island, and Mullet Island are shown on the base map and make ideal monuments while working in that area.

There are a series of large water tanks along the hill tops that border the eastern side of the lake. None of these were shown on any of the U.S.G.S. topographic maps or the base map. With the aid of aerial photographs, several of the tanks were plotted on the base map and these with such features as the Bat Caves Buttes and Salt Creek formed the best locations in the central and northern part of the lake.

Much of the development on the western side of the lake came about after the available topographic maps were published. Since the maps were issued, the lake level has risen and the shore line has changed, so many prominent structures, such as marinas where piers and breakwater changed the previous shore line were a problem to locate.

Visibility varied considerably, ranging from very clear, when a person could easily see Mt. San Jacinto and Mt. San Gorgonio on the north and several mountains in Mexico to the other extreme which found us unable to see any shore from the middle of the lake. Under conditions of poor visibility, horizontal sextant bearings which require three distinct, well located features, were not possible. Under these conditions, only compass bearings and dead reckoning were used, and moderate errors probably resulted.

Anchoring Methods

When located at each station, the boat was anchored with about twice to three times as much chain and line as the water depth. We went to the Salton Sea with only one anchor and planned to use an anchor-like cone dredge if additional position stability was needed. It was not realized how quickly the wind can come up or how frequently it would change direction.

At station 18, on a day when we had only a two man crew, the boat was anchored under calm conditions and the probe lowered and in the bottom. Both members of the study team were very occupied with reading instruments and recording data and not paying attention to the conditions of the lake. A sudden strong wind changed the direction and position of the boat, and before we knew it, the boat was dragging anchor. Eventually the anchor line was fouled with the probe line and it was a real problem trying to maneuver the boat against the wind and three lines to get it over the probe for recovery. Because of this event data from subsequent stations 19, 20, and 21 were subject to uncertainty.

It was eventually found necessary to use the anchor, the cone dredge and several lengths of heavy chain as an auxiliary stern anchor and even use the corer which proves to be a good anchor.

After anchoring the depth was crudely measured using a fishing rod with knots tied every ten feet. Between knot intervals were estimated. Errors in this estimation could amount to two feet. At this time the exact depth was considered unimportant and although measured, it was frequently not recorded.

Thermal Measuring Equipment

The thermal measuring equipment was described in a preceding paper by Wilde and others. During this study only the unarmored fiberglass probes were used.

Considerable difficulty and uncertainty were caused by breaking the probe on station 22. This may have resulted from procedures rather than equipment design.

To lower the probe required one man on the winch and one man unspooling the electrical control line. The cable ran over a 2-inch diameter roller, and it was frequently necessary to realign the cable on the roller or on the winch level wind guide. For later studies a davit greatly improved handling the probe and cable.

Once the probe was in bottom, the procedure was to wait about 10 minutes and make three runs of bridge mode, low voltage (about .4000 volts) readings, then three runs of carefully timed direct mode high voltage (12.000 volts) readings. Then the probe was recovered and inspected.

The probe usually showed variable sediment. Typically red-brown firmer and sometimes sandy mud at the base and soft light gray mud to near the top with the uppermost part dark gray or black mud frequently with barnacle fragments. The brown sediment is thought to be pre-lake playa sediment while the barnacles first came to the lake in the 1940's. Cores were collected at each station, usually while waiting for the probe to equilibrate. Most cores were about 16 or 18 inches in length, so the cored interval represents less than half of the interval penetrated by the probe. On Mono Lake the corer weight was doubled and much longer cores were recovered.

Using the above procedures the base station was measured seven times and single measurements were made at 52 other stations during the study period. During a normal day we measured temperatures at about seven stations. About half of the time was spent getting from station to station and half the time spent measuring.

During this study, there was no method to make field checks of temperatures. All that was available for checks were meter readings, and they differed from station to station with water temperature, and at that time the bridge voltage

was merely recorded and not tuned, so readings also varied with bridge voltage. During studies of other lakes, direct mode measurements using a carefully tuned voltage and an available calibration table.

Data Reduction

Following the field work, all of the data collected were computed by J. Oldson who had prepared a program that calculates the temperature in degrees celsius at each thermistor, the difference between thermistors, the gradient extrapolated degrees per kilometer and the heat flow based on assumed conditions.

Data from all measurements have been analyzed and evaluated. Because of apparently inconsistent time allowances for thermal equilibration for some stations, the third run or set of bridge mode temperatures were used. But comparisons were made between the third set temperatures and those of the first and second sets as a check against gross errors and to evaluate instrumental variability. For many stations, all three sets of temperature readings could have been used with the advantage of the improved confidence obtained from using the mean of three readings rather than a single measurement. But it appeared that some stations were measured without allowing proper equilibration time. It may be that the variability of sediment types from station to station requires different equilibration times.

Measurements at the Base Station

Measurements at the base station (station 3) were made on seven days. Figure 2 shows temperature measurements for T2 and for the water thermistor (T_w).

The water temperatures follow a linear curve with very limited deviation except for March 18, the day on which Probe 1 was broken. Probe 2 data fit well with the Probe 1 curve until Probe 2 became erratic, mostly occurring on the last day of measurements.

FIGURE 2.

The sediment temperature at the base station apparently did not vary during the study. T-2 was used for the sediment curve because it is less likely to have compounded measurement errors. All readings on low voltage except T-2 were made in the bridges mode with T-2 as the reference thermistor.

T-1 was over a degree higher for Probe 2 than for Probe 1. Probe 2 became erratic with time, but was most erratic on the last day of measurement when data sheets say "very erratic" for 40-13 and " $\pm .4$ " (millivolts) for 40-14 for thermistor 4. The previous days notes were " $\pm .1$ " (millivolts) for T-4. This suggests that 40-9 to 40-16 readings may be unreliable. However, plotting the data for TW and T-5 show temperature differences that closely match expected temperatures for the water depth.

Thermal Measurements

Temperature data for all stations are shown on Figure 3. Four temperatures are plotted for each station. Data for all thermistors are uncertain for stations 19, 20, 21. Thermistor 4 appears the least reliable overall. This thermistor reads much lower on Probe 2 than Probe 1 and shows inconsistent readings in the sediment. Probe 1 broke at this thermistor. Thermistor 1 data are only fair at best. It shows wide dispersion and Probe 2 readings are more than a degree higher than Probe 1 readings. Data for thermistor 3 and 5 appear the most reliable, those for the water temperatures and the temperatures at thermistor 2 are fair to good. These four thermistors were used to plot figure 3.

Throughout the study the precise probe-bottom relationship was uncertain. The depth was only crudely measured with a sounding line, but the cable wasn't metered. There was always some uncertainty about penetration and penetration isn't a controllable factor. Where the bottom was soft, the probe appears to penetrate easily.

FIGURE 3

LEGEND
TEMPERATURE °C
T-2
TW • T-3
T-5

When the probe is recovered with mud covering the weights, one could be sure it had fully penetrated. In the brown unit, which may represent pre-lake sediment, penetration was variable and the firmness of this unit probably minimized penetration.

Station 6 is an example of the effects of non-penetration. It was marked as "possibly non-penetration, mud to T-3, usually mud higher!!" The temperature of T-1 at this station was 15.60°C. But it was 17.33 at station 5 and 17.78°C at station 4. The temperature measured for T-1 at Station 6 is about what would be expected for say T-4.

Model of Seasonal Effects

Based on an assumption of uniform thermal conductivity, thermal diffusivity, and sine wave form variation, a mathematical model of the seasonal variation in bottom temperature due solar effects was computed for the Salton Sea by J. Oldson. The maximum and minimum temperatures used were 34.5°C and 12.0°C, thermal conductivity = .0018 and diffusivity = .0021. The program for this model is described in a previous report by Wilde and others, this volume.

At the time of this study the temperatures predicted by the model were: water temperatures ranging from 15.295°C at month 7.5 (about March 15) to 17.625°C during month 8.0 (about April 1), or changing 2.33° during one-half month. The greatest temperature change occurs in the water and the rate of change diminishes with depth in the sediment. For T-5 the predicted change is from 15.433°C at month 7.5 to 17.230°C at month 8.0 or a 1.797° C change over one-half month. The change for T-1 was less than one-fifth that of T-5 and was 0.334°C over one-half month. The following table shows the predicted temperatures calculated by John Oldson for month 7.5.

TABLE I

Probe 1 (Used March 13-18)

<u>Thermistor</u>	<u>Temperature (°C)</u>	<u>Gradient (°/Km)</u>	<u>Heat Flow (H FU)</u>
T1	17.625°	3416°	61.5
T2	16.942°	3126°	56.3
T3	16.317°	2609°	47.0
T4	15.795°	1814°	32.6
T5	15.433°	687	12.4
Tw	15.295°		

Field Data and the Seasonal Heating Model

There is good agreement between the model of seasonal heating variations and field measurements. Table 2 makes a comparison between the mean of all Probe 1 stations where the probe had fully penetrated except for station 14, which is a hot spring and stations where the probe was erratic.*

TABLE 2Seasonal Model, Month 7.5Mean of Probe 1 Stations*

<u>Thermistor</u>	<u>Temperature</u>	<u>Temperature (°C)</u>
T1	17.62°	17.58°
T2	16.94°	16.92°
T3	16.32°	16.17°
T4	15.79°	15.95°
T5	15.43°	15.83°
Tw	15.29°	15.51°

* Stations excluded are #6, 11, 14, 19, 20, 21.

These data indicate that apparently high thermal gradient and heat flow will be measured at most or all of the stations.

The variability due to change in seasonal effects is high and variability due to sediment characteristics is probably high. So, there is great uncertainty as to what actually represents geothermal heating. Since the mean of all stations almost coincides with the seasonal model, about half of the stations will have higher temperatures than the model. Because most of the solar effects are accounted for by the model, any stations that are considerably higher than the mean possibly represent geothermal heating.

This would obviously include station 14 which has a highest temperature of 47.37°C for the deepest penetration and a uniform gradient to thermistor 5 which measured 25.34°C indicating a gradient of 27,530°/Km when extrapolated. It is interesting to note that the water temperature of 16.88° is actually less than nearby station 11, which is shallower.

Other than station 14 recognition of geothermally anomalous stations becomes difficult. With respect to the seasonal heating model, the assumptions of uniform conductivity and diffusivity may not be justified. The cores are distinctly layered and the character of the bottom, such as grain size, differs from the near shore to mid-lake areas. Sediment descriptions were not made at every station, but where they were made and the sediment was described as layered, there were frequently marked temperature changes. An example of this is station 15 where a layer of light brown sandy mud was described as occurring at the third thermistor with a light gray soft mud above it. This lense had a lower temperature than the adjacent gray clay resulting in +274 heat flow units being calculated for the interval between T2 and T3, then -209 heat flow units between T3 and T4. The sandy unit described

above probably differs considerably from a unit described as firm red brown clay which was frequently found on the probe near the lower part and has been assumed to be pre-lake sediment. It was usually overlain by light gray very soft clayey mud. This unit has variable thickness and usually has a lower temperature than the brown unit. The brown unit is firmer, and it probably minimized penetration.

It can be seen by the model in Table 1 that at this time of year, the further the probe penetrates, the higher the temperatures and the thermal gradient. The probe may penetrate as much as 135 cm to the plate at the top of the weight stand or perhaps only half that distance. This would cause an apparent change in the thermal gradient of about $1000^{\circ}/\text{Km}$.

In an effort to sort out any stations other than station 14 that have signs of geothermal heating a tabulation was made of all stations higher than the mean. The question then becomes how much higher than the average should a station be to suggest geothermal heating? As a preliminary estimate all stations $.3^{\circ}\text{C}$ higher than the average were noted for each thermistor for both probes. Data from Probe 2 were considered but using a separate mean for each probe. For Probe 2, thermistor 1 and thermistor 4 are obviously different from Probe 1, but their dispersion isn't much greater. Station 40 was represented by 40-6 which was drawn by lottery from all of the location 40 stations.

Many of the stations were noted as having higher than average temperatures for most of the thermistors. This would be an unlikely occurrence because of random effects, geothermal heating being a more likely possibility. Of the stations listed for Probe 1, station 8 appeared on the list for each thermistor and had the highest temperature other than station 14 for four of the five thermistors. Stations 12 and 17 were cohighs for the other thermistors. Station 9 also appeared on the above average temperature list for all thermistors. Stations 12 and 17 appeared on four of five

lists, and stations 4 and 13 on three of five lists.

There is uncertainty about the reliability of all Probe 2 data, but the base station data, up to the last day, fit well with Probe 1 data. Also, the overall temperature distribution from three of the five thermistors fit within the distribution for Probe 1. Only T-1 appears aberrant because it consistently reads higher than Probe 1. The mean difference between Probe 1 and Probe 2 for thermistor 1 is 1.39°C.

Treating Probe 2 stations as a separate population, station 35 is consistently high and stations 25, 31, and 40 are high on 4 of 5 thermistors, and 28 and 30 on 3 of 5.

Probe 1 stations 18, 19, and 20 may be unreliable due to probe failure, but these stations appear to have higher than normal temperatures and high heat flow.

When the higher than average stations indicated above are plotted on the map, it is found that they cluster into three areas.

The most important and largest area is found in the southeastern part of the lake. It extends from station 14 about 6 or 7 nautical miles to station 7 with the width of the area from station 9 to 13. It forms a northwestward trending semi-elliptical area of about 17 square nautical miles. This area is defined by 8 stations with well higher than average temperatures. This area was expected to have high geothermal characteristics based on other geophysical data. Thus the measurements in the lake somewhat complement the previous geophysical data to suggest a more or less symmetrical area centered on the young volcanic buttes at the south end of the lake. The westward extent of the area is unknown for lack of measurements.

The absence of stations 10 and 11 from this apparently positive geothermal area is probably less expectable than the inclusion of any other stations because these stations are the closest to known upland geothermal areas. Both stations have subnormal temperatures and lower than average gradients. Field notes for station 11 suggest incomplete penetration. Also, high water temperature was noted.

The proximity of the Alamo River suggests a high sedimentation rate and probably unusual conditions of sedimentation. Fresh water springs or underground flow may greatly distort the regional conditions.

There are two other areas with possibly anomalous geothermal heating. One area in the central part of the lake is defined by three apparently higher than normal temperature, high gradient stations. The validity of these stations is somewhat questionable because of possible mechanical failure of the probe. The other, more northerly area, is shown by four high temperature stations. This area was measured using Probe 2. But these stations were measured before most of the erratic instrumental readings appeared for Probe 2.

If these anomalies are real, there is a hint of a long, perhaps discontinuous zone trending northwestward along the major axis of the lake.

ACKNOWLEDGEMENTS

Co-Investigator for this study was R. C. Martin. Field assistance was provided by G. C. Crow, D. W. Moore, D. L. Hoagland, and R. E. MacColl. F. E. Knight provided help ranging from construction of equipment, advice on working on the Salton Sea, made weather checks, and maintained hourly seashore radio communication. N. E. Welday provided logistical support. T. C. Lee made suggestions on equipment and procedures and with L. Cohen and other guests from University of California, Riverside, spent the first day of the study working on the lake.

Thermal measuring equipment were designed and constructed by the Lawrence Berkeley Laboratory. P. Wilde and J. C. Oldson delivered and set up the equipment and provided instruction on field use. J. C. Oldson computed all field data and mathematically modelled the solar heating seasonal effects.

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SPHERICAL FLOW
IN
NATURALLY FRACTURED RESERVOIRS

by

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August 17, 1976

SPHERICAL FLOW IN NATURALLY FRACTURED RESERVOIRSABSTRACT

A method has been developed for determination of certain characteristics of naturally fractured reservoirs under a spherical flow regime. Spherical flow develops when producing wells are "nonpenetrating", i.e., the wells penetrate only a small distance into a massive formation, Figure 1.

Mathematical modeling done in this study is for a double-porosity system where the reservoir is assumed to consist of a matrix system and a fracture network. Fractures are assumed to be orthogonal and with high fluid flow capacity. The matrix system, on the other hand, is visualized as a system which has high fluid capacitance with very little fluid flow capacity.

The fundamental differential equation describing the above system is solved by the application of the Laplace Transformation. A method is then presented for the estimation of an average spherical permeability and static reservoir pressure. Also, a procedure is discussed for the estimation of total fluid capacitance of a reservoir and the fraction contributed by the fracture network.

Description of the Reservoir Problem

The steam production in The Geysers area is believed to be from a naturally fractured reservoir. Furthermore, the wells penetrate only a small distance into the massive reservoir. This limited penetration creates a spherical flow regime.

Several pressure buildup tests have been run on some of the wells in The Geysers area. Methods employed so far in interpreting the data are all based on the assumption of radial flow geometry. The radial flow model is incapable of

generating permeabilities in such systems. This is because of two reasons. First, a knowledge of total thickness is required before the horizontal permeability can be obtained from permeability thickness product. Secondly, geology of the area indicates the vertical movement of the fluid to be the dominant one.

Mathematical models for interpretation of pressure buildup data in nonfractured reservoirs such as the methods developed by Moran and Finklea,^{1 2} Chatas,³ and Culham are available in the literature. Furthermore, methods for analysis of well test data in naturally fractured reservoirs under radial flow have been presented by Pollard,⁴ Warren and Root,^{5 6 7} Odeh, and Kazemi. No work has yet been reported, however, for naturally fractured reservoirs under spherical flow.

The purpose of this study was to develop a mathematical model and utilize the results for establishment of a procedure for estimation of the properties of a naturally fractured reservoir where the flow regime is spherical.

Reservoir Model

The Warren and Root Model, consisting of a double-porosity system, is employed in this study. In this model the reservoir is assumed to have two types of distinct porosities, matrix region and fracture network. The matrix contains fine pores and usually has high storage capacity with negligible flow capacity. The fracture network, however, has low storage capacity and large flow capacity. Warren and Root developed their equations for cylindrical flow conditions. They assumed a horizontal and an isotropic reservoir and defined an average permeability to represent the fracture network. The average permeability was defined as the geometric mean of the directional permeabilities.

In this case, an orthogonal fracture network system is still considered with the modification that the flow is given a vertical component. It is also assumed that an average spherical permeability describes the flow capacity of

the system. The wellbore is assumed to be nonpenetrating. This precludes the existence of any radial flow regime. For an infinite reservoir with a uniform initial pressure "P_i" which is produced at a constant rate of "q", the problem could be expressed by finding a solution to the following equations:

$$(1) \quad \frac{\partial^2 P_2}{\partial r^2} + \frac{2}{r} \frac{\partial P_2}{\partial r} = \frac{\mu}{k_2} \left(\phi_1 C_1 \frac{\partial P_1}{\partial t} + \phi_2 C_2 \frac{\partial P_2}{\partial t} \right)$$

$$(2) \quad \phi_1 C_1 \frac{\partial P_1}{\partial t} = \alpha \frac{k_1}{\mu} (P_2 - P_1)$$

with the boundary conditions listed below:

$$P_1 = P_2 = P_i \quad \text{at } t = 0 \text{ for } 0 < r < \infty$$

$$\left[r \frac{\partial P_2}{\partial r} \right]_{r=r_{ew}} = \frac{q \mu}{2 \pi k} \quad t > 0$$

$$\lim_{r \rightarrow \infty} P_2 = P_i \quad t > 0$$

$$r \rightarrow \infty$$

In the above equations, subscript 1 refers to matrix system and subscript 2 to the fracture network. Equation (1) is basically the flow equation for the reservoir and equation (2) describes the fluid flow from the matrix region into the fracture network.

Solution of the Equations

Using the following dimensionless variables, the above equations and the initial and boundary conditions can be shown in dimensionless form as listed below:

$$P_D = 2 \pi \bar{k}_2 r_{ew} \frac{(P_i - P)}{q \mu B}$$

$$t_D = \frac{\bar{k}_2 t}{(\phi_1 C_1 + \phi_2 C_2) \mu r_{ew}^2}$$

$$r_D = \frac{r}{r_{ew}}$$

$$(3) \quad \frac{\delta^2 P_{D2}}{\delta r_D^2} + \frac{2}{r_D} \frac{\delta P_D}{\delta r_D} = \lambda (P_{D2} - P_{D1}) + \omega \frac{\delta P_{D2}}{\delta t_D}$$

$$(4) \quad P_{D1} = P_{D2} = 0 \text{ at } t_D = 0 \quad 0 < r_D < \infty$$

$$(5) \quad \left[\frac{\delta P_{D2}}{\delta r_D} \right]_{r_D=1} = -1 \quad t_D > 0$$

$$(6) \quad \lim_{r \rightarrow \infty} P_{D2} = 0 \quad t_D > 0$$

Where:

$$\omega = \frac{\phi_2 C_2}{\phi_1 C_1 + \phi_2 C_2}$$

$$\lambda = \alpha \frac{k_1}{\bar{k}_2} r_{ew}^2$$

The symbol "ω" represents the fraction of total storage contributed by the fracture network. The symbol "λ" is called the interporosity flow coefficient and is a

measure of the permeability ratio between the matrix and the fracture regions. Application of the Laplace transformation to equations (3) through (6) will result in the elimination of P_{D1} and the following equation is obtained:

$$(7) \quad \frac{\delta \bar{P}_{D2}}{\delta r_D} + \frac{2}{r_D} \frac{\delta \bar{P}_{D2}}{\delta r_D} = s \cdot f(s) \cdot \bar{P}_{D2}$$

Where:

$$\bar{P}_{D2} = \int_0^{\infty} e^{-s \cdot t_D} P_{D2}(r_{D1}, t_D) dt_D$$

$$f(s) = \frac{\omega(1-\omega) + \lambda}{(1-\omega)s + \lambda}$$

the solution to equation (7) is:

$$\bar{P}_{D2} = \frac{1}{r_D} s \cdot f(s) \left[C_1 \cdot e^{r_D \sqrt{s \cdot f(s)}} - C_2 e^{-r_D \sqrt{s \cdot f(s)}} \right]$$

Applying the boundary conditions of:

$$\left[\frac{\delta \bar{P}_{D2}}{\delta r_D} \right]_{r_D=1} = -\frac{1}{s}$$

$$\lim_{r_D \rightarrow \infty} \bar{P}_{D2} = 0$$

will result in:

$$(8) \quad \bar{P}_{D2}(r_D, s) = \frac{1}{r_D} \cdot \frac{1}{s} \cdot \frac{1}{\sqrt{s \cdot f(s)} + 1} e^{-(r_D - 1)\sqrt{s \cdot f(s)}}$$

To obtain an inversion for the dimensionless pressure drop at the well bore (i.e., $r_D = 1$), the following cases are considered. For all these approximations, it must be kept in mind that " λ " is a very small number.

Early Times Solution

$$(9) \quad \lim_{t_D \rightarrow 0} f(s) = \omega$$

$$\bar{P}_{D_2}(1, s) = \frac{1}{s} \cdot \frac{1}{\sqrt{\omega s + 1}}$$

The inversion of equation (9) is:

$$(10) \quad P_{D_2}(1, t_D) = 1 - e^{-\frac{t_D}{\omega}} \operatorname{erfc} \sqrt{\frac{t_D}{\omega}}$$

Early to Middle Times Solution

$$\bar{P}_{D_2}(1, t_D) = \int_{-1}^{\infty} \frac{1}{s} \cdot \frac{1}{\sqrt{s \cdot f(s) + 1}}$$

One can expand the function of S into a power series in λ . After finding the inverse Laplace transform, the result is:

$$(11) \quad P_{D_2} = 1 - e^{-\frac{t_D}{\omega}} \operatorname{erfc} \sqrt{\frac{t_D}{\omega}} + \lambda \left[-\sqrt{\frac{t_D}{\pi \cdot \omega}} + \frac{(t_D - 1)}{\omega} \right]$$

$$+ e^{-\frac{t_D}{\omega}} \operatorname{erfc} \sqrt{\frac{t_D}{\omega}} + \lambda^2 \left[\frac{1}{4} \left(2 \sqrt{\frac{(t_D)^3}{\omega \pi}} - 12 \sqrt{\frac{t_D}{\omega \cdot \pi}} \right) \right]$$

$$\begin{aligned}
& + \frac{t_D}{\omega} + 6 + \left(-6 + 5 \frac{t_D}{\omega} - 2 \left(\frac{t_D}{\omega} \right)^2 \right) \left(e^{\frac{t_D}{\omega}} \operatorname{erfc} \sqrt{\frac{t_D}{\omega}} \right) \\
& + \frac{4}{4} \frac{v+1}{4} \left[2 \sqrt{\frac{t_D}{\pi \cdot \omega}} \left(\frac{t_D}{3 \cdot \omega} + 2 \right) - \frac{t_D}{\omega} - 2 \right. \\
& \left. + \left(2 - \frac{t_D}{\omega} \right) e^{\frac{t_D}{\omega}} \operatorname{erfc} \sqrt{\frac{t_D}{\omega}} \right]
\end{aligned}$$

Where:

$$v = \frac{\omega}{1 - \omega}$$

This equation can be numerically evaluated for any assumed values of " ω ".

Figure 2 shows some typical curves for different values of " ω ", all of which were computed for $\lambda = 0.000001$.

An important feature of the spherical solution is that unlike the cylindrical flow formula the middle times solution is not significantly affected by " λ ". As an example, the computed values of dimensionless pressure drop for $\omega = 0.1$ and several values of " λ " are listed in Table 1. The differences are negligible for practical application.

Late Times Solution

The onset of pseudo steady state condition is represented by the late times solution.

$$\lim_{t_D \rightarrow \infty} f(s) = 1$$

$$t_D \rightarrow \infty$$

$$(12) \quad P_{D2}(1, s) = \frac{1}{s} \cdot \frac{1}{\sqrt{s+1}}$$

The inversion of equation (12) yields:

$$P_{D_2}(1, t_D) = 1 - e^{-t_D} \operatorname{erfc} \sqrt{t_D}$$

The late times solution is essentially the same as presented by Chatas for a homogeneous system. In fact, the above solution indicates that for the reservoir model used, the late times data will result in a behavior similar to that of an unfractured reservoir. Middle times solution, however, reflects the storage properties of the double porosity system when the matrix feeds the fracture system. The early times behavior with a slope of 0.5 indicates the fluid flow from the fracture network is linear.

Application of the Solutions

In terms of real pressure and real times and assuming no skin around the well bore, the late times solution can be shown as follows:

$$P_D = 1 - e^{-t_D} \operatorname{erfc} \sqrt{t_D} \approx 1 - \frac{1}{\sqrt{\pi \cdot t_D}}$$

$$(13) \quad P_{wf} = P_i - 141.2 \frac{q \mu B}{\bar{k}_2 r_{ew}} \left(1 - \sqrt{\frac{(\phi_2 C_2 + \phi_1 C_1) \mu r_{ew}^2}{13.82 \times 10^6 \bar{k}_2 t}} \right)$$

Where r_{ew} is an equivalent well bore radius given below (see Moran and Finklea and Culham)

$$(14) \quad r_{ew} = \frac{hc}{2 \ln \left(\frac{hc}{r_w} \right)}$$

Equation (13) is applicable to analysis of pressure fall-off tests. For pressure buildup testing, the principle of superposition should be applied to the above equation. This process simply means superimposing the effect of shutin period on the pressure performance of a well which has been producing at a constant rate of q and for a period of t .

After the application of the principle of superposition the following equation can be obtained.

$$(15) \quad P_{ws} = P_i - m \left(\frac{1}{\sqrt{\Delta t}} - \frac{1}{\sqrt{t + \Delta t}} \right)$$

where:

$$(16) \quad m = 38002 \, qB \left(\frac{\mu}{\bar{k}_2} \right)^{\frac{3}{2}} \sqrt{(\phi_2 C_2 + \phi_1 C_1)}$$

Equation (15) indicates that a plot of P_{ws} vs. $\left(\frac{1}{\sqrt{\Delta t}} - \frac{1}{\sqrt{t + \Delta t}} \right)$

should result in a straight line with a slope as defined by equation (16). Extrapolation of this straight line to infinite shutin time, i.e., $\left(\frac{1}{\sqrt{\Delta t}} - \frac{1}{\sqrt{t + \Delta t}} \right) = 0$ will result in P^* .

Also, equation (16) provides a relationship between $\bar{k}_2$ and $(\phi_2 C_2 + \phi_1 C_1)$.

Estimation of $\bar{k}_2$, $(\phi_2 C_2 + \phi_1 C_1)$, and ω

Two methods for estimation of above parameters are presented. The first method is applicable to the case where the skin damage around the wellbore is assumed to be nonexistent. This is perhaps the case applicable to most fractured reservoirs. Under the existence of skin damage a different method is proposed and will be discussed later.

Case 1. $S = 0$

The solution to the partial differential equation describing the double-porosity system discussed in this paper indicates that under a spherical flow regime the upper bound of the dimensionless pressure fall-off or buildup is unity. For field cases, the upper limit is $\Delta P^* = P^* - P_{wf}$. Thus, a dimensionless pressure fall-off buildup of unity is equivalent to ΔP^* . Substituting $P_D = 1$ and $P_i - P = \Delta P^*$ in the dimensionless pressure equation and using oil field units the following equation can be obtained.

$$P_D = 2\pi \bar{k}_2 r_{ew} \frac{(P_i - P)}{q\mu B}$$

$$(17) \quad \bar{k}_2 = \frac{141.2 q\mu B}{\Delta P^* \cdot r_{ew}}$$

Now equation (16) can be utilized for computation of total fluid capacitance:

$$(\phi_2 C_2 + \phi_1 C_1) = \left(\frac{m}{38002 qB \left(\frac{\mu}{\bar{k}_2} \right)^{\frac{3}{2}}} \right)^2$$

Where m is the slope of the straight line portion of the late times data.

Determination of " ω " can be made by using the master type curve plot. A transparent paper should be placed on the master plot. After drawing the major axis of the log - log scale on the transparent paper, a plot of ΔP vs. Δt should be made on the paper. By overlaying the line representing $\Delta P = \Delta P^*$ on $P_D = 1$ and sliding the field curve over the master type curve, the proper " ω " can be obtained. Obviously there is a unique solution. Such solution must result in t_D values corresponding to actual Δt 's as predicted by the following equation:

$$t_D = \frac{4.4 \times 10^{-6} \bar{k}_2 \Delta t}{(\phi_2 C_2 + \phi_1 C_1) \mu r_{ew}^2}$$

Case 2. $S \neq 0$

In the presence of skin damage, a trial and error method needs to be used for determination of reservoir properties. First, an estimation of total fluid capacitance $(\phi_2 C_2 + \phi_1 C_1)$ for the reservoir is needed. This could be obtained from porosity and compressibility data for the reservoir rock and fluid respectively. Using the total fluid capacitance in equation (16), a value for $(\bar{k}_2)_a$ can be computed. Now using equation (17) the pressure drop (ΔP^*) corresponding to $P_D = 1$ can be obtained. Following a similar procedure as outlined in case (1) a value for " ω " can be selected. Now any point of the actual data and its corresponding P_D would provide a value for $(\bar{k}_2)_c$ according to the following equation:

$$(18) \quad (\bar{k}_2)_c = \frac{141.2 q \mu B \cdot P_D}{\Delta P \cdot r_{ew}}$$

If $(\bar{k}_2)_a = (\bar{k}_2)_c$, the initial assumption of $(\phi_2 C_2 + \phi_1 C_1)_a$ is acceptable and the reservoir unknowns have been determined. Otherwise, another estimate should be made for the total fluid capacitance and by repeating the process a satisfactory set of parameters can be obtained. This may take two to three trials.

Development of Skin Factor Equation

Equation (13) is valid only if $S = 0$. In the presence of skin, a more general form of the equation is:

$$(19) \quad P_{wf} = P_i - D \left(1 - \frac{1}{\sqrt{\pi t_D}} \right) + S$$

where:
$$D = 141.2 \frac{q \mu B}{\bar{k}_2 r_{ew}}$$

for the pressure buildup case:

$$(20) \quad P_{ws} = P_i - D \left[\frac{1}{\sqrt{\pi t_D}} - \frac{1}{\sqrt{\pi (t_D + \Delta t_D)}} \right]$$

Combining equations (19) and (20) results in the following expression for the skin factor:

$$S = -1 + \frac{P_{ws} - P_{wf}}{D} + \sqrt{\frac{(\phi_2 C_2 + \phi_1 C_1) \mu r_{ew}^2}{13.82 \times 10^{-6} k_2}} \left[\frac{1}{\sqrt{t}} + \frac{1}{\sqrt{\Delta t}} - \frac{1}{\sqrt{t + \Delta t}} \right]$$

If Δt is chosen small enough so that $t + \Delta t \approx t$, then S can be expressed as follows:

$$(21) \quad S = \sqrt{\frac{(\phi_2 C_2 + \phi_1 C_1) \mu r_{ew}^2}{13.82 \times 10^{-6} k_2}} \left[\frac{P \Delta t - P_{wf}}{m} + \frac{1}{\sqrt{\Delta t}} \right] - 1$$

where Δt is in minutes and m in $\text{psi} - \sqrt{\text{min}}$.

In metric units and for a steam well, the equation becomes:

$$(22) \quad S = \sqrt{\frac{(\phi_2 C_2 + \phi_1 C_1) \mu r_{ew}^2}{1.132 k_2}} \left[\frac{P \Delta t - P_{wf}}{m} + \frac{1}{\sqrt{\Delta t}} \right] - 1$$

Application of the Proposed Technique

The step-by-step procedure presented below is provided for the analysis of pressure data for geothermal steam wells. Considering steam as a gas with a molecular weight of 18 and modifying the equations to work with metric system, the following equations and procedures are applicable:

- 1 - Estimate $(\phi_2 C_2 + \phi_1 C_1)_a$

2 - Compute $(\bar{k}_2)_a$, as shown below:

$$(\bar{k}_2)_a = \frac{4.046 \text{ TZq } (\mu)^{\frac{3}{2}}}{m} (\phi_2 C_2 + \phi_1 C_1)^{\frac{1}{2}}$$

3 - Compute ΔP^{*2}

$$\Delta P^{*2} = \frac{4.303 \text{ q}\mu\text{ZT}}{(\bar{k}_2)_a r_{ew}}$$

4 - Find t_D for a certain Δt :

$$(t_D)_M = \frac{.3604 (\bar{k}_2)_a}{(\phi_2 C_2 + \phi_1 C_1) \mu r_{ew}^2} (\Delta t)_M$$

5 - Find the proper ω curve by sliding the field data over the type curves until ΔP^{*2} overlaps $P_D = 1$ and $(\Delta t)_M$ matches $(t_D)_M$. Read $(P_D)_M$ at the value of $(\Delta t)_M$.

6 - Compute $(\bar{k}_2)_c$

$$(\bar{k}_2)_c = \frac{4.303 \text{ q}\mu\text{ZT } (P_D)_M}{(\Delta P^{*2})_M r_{ew}}$$

where (ΔP^{*2}) corresponds to field data at $\Delta t = (\Delta t)_M$

7 - Compare $(\bar{k}_2)_c$ with $(\bar{k}_2)_a$. If the two are not sufficiently close, repeat the procedure until a satisfactory match is obtained.

Example Calculation

The following example is presented to demonstrate the utility of the proposed technique to practicing engineers. The example is based on pressure buildup data on a steam well published by Ramey and Gringarten. In the absence of

tabulated values of pressure data, the graphs were used to extract the following buildup data:

<u>Δt, hrs.</u>	<u>P_{ws}^2, kg/cm²</u>
0.0164	89.75
0.0270	94.90
0.0485	108.60
0.0666	115.50
0.1430	145.20
0.2460	168.50
0.3380	190.00
0.4850	214.00
0.7290	251.00
1.2500	298.00
2.0500	366.00
4.2400	442.00
10.0000	595.00
13.7000	668.00
17.9000	737.00
22.5000	752.00
27.0000	814.00
33.8000	830.00
40.5000	847.00
48.5000	882.00
55.6000	900.00
69.6000	937.00
79.7000	956.00

<u>Δt, hrs.</u>	<u>P_{ws}^2, kg/cm²</u>
91.3000	976.00
114.0000	996.00
140.0000	1011.00
157.0000	1037.00
205.0000	1081.00

Additional test data are:

Well bore radius	.122, m
Steam flow rate	51.8 ton/hr.
Flowing time	5112 hrs.
Reservoir temperature	452.8° K
Steam viscosity	0.023 CP
Gas deviation factor	0.928
Thickness of the open interval	938.7, m

Ramey and Gringarten applied the radial flow concept and concluded the permeability thickness product of the formation to be 6.91 darcy-meters. As shown in Fig. 3 the Horner plot of the data indicates the presence of skin. Most likely, however, the pseudo skin depicted on the plot is because of the partial penetration of the well. Fig. 4 is the type curve for the well. Notice the early times data shows a 0.5 slope indicating linear flow.

The plot of the shutin pressure vs. $\frac{1}{\sqrt{\Delta t}} - \frac{1}{\sqrt{t + \Delta t}}$

is shown in Fig. 5. The late times data result in a straight line with a slope of $4700 \text{ (kg/cm}^2\text{)}^2 - \sqrt{\text{hr.}}$. From the extrapolation of this line $P^* = 36.7 \text{ kg/cm}^2$. In terms of oilfield units this indicates a static reservoir pressure of 539 psi.

Now an assumption is made for total fluid capacity and the procedure outlined in this report is followed. Table 2 shows a summary of the computations. The third trial resulting in a satisfactory match indicates:

$$\bar{k}_2 = 0.009 \text{ darcy}$$

$$\omega = 0.7$$

$$S = 0.09$$

The average spherical permeability of 0.0337 darcy obtained above is clearly much larger than the horizontal permeability of the formation. The permeability-thickness product of 6.91 darcy - m requires a permeability number much smaller than 0.0337 darcy to result in a realistic formation thickness larger than the completion thickness. Thus one may conclude that the contribution of the vertical permeability to the overall magnitude of the average spherical permeability for the above example has been very significant; i.e., most of the steam has moved toward the wellbore from down deep.

The total fluid capacitance has been determined to be $0.009 \text{ (kg/cm}^2\text{)}^{-1}$. Assuming a single phase (steam) fluid in both the matrix and the fracture system, for average reservoir pressure (between P^* and P_{wf}), the steam compressibility is estimated to be about $0.0426 \text{ (kg/cm}^2\text{)}^{-1}$. Type curve matching of the data indicates that " ω " is very close to unity. Using $\omega = 1$, the conclusion is that almost all the fluid is stored in the fracture network. From the above values of compressibility and total fluid capacitance a porosity of 0.21 can be estimated for the reservoir.

Skin factor calculations indicate a skin factor very close to zero which is more representative of the wellbore conditions than what the Horner plot indicates.

The above example shows the significant reservoir parameters which could be obtained by applying the proposed technique to pressure data in a nonpenetrating well draining a naturally fractured reservoir.

Summary and Conclusions

The pressure transient behavior of naturally fractured reservoirs with spherical flow regime has been studied using a double-porosity model. The findings may be described as follows:

1. For a thick naturally fractured reservoir where the well penetrates only a small portion of the reservoir, the pressure buildup or fall-off data could result in a 0.5 slope on a log-log plot of ΔP vs. Δt for the early times region. After that the pressure buildup or fall-off gradually approaches a finite value equivalent to ΔP^* . The late times data plotted vs.

$$\left(\frac{1}{\sqrt{\Delta t}} - \frac{1}{\sqrt{t + \Delta t}} \right)$$

results in a straight line. Extrapolation of the straight line to infinite shutin time will provide a value for P^* (static reservoir pressure). The slope of this straight line establishes a relationship between average spherical permeability and the total fluid capacitance. Using a type curve matching procedure discussed in this report, the value of $\bar{k}_2$ (average spherical permeability), $\phi_2 C_2 + \phi_1 C_1$ (total fluid capacitance), and ω (fraction of total storage contributed by the fracture network) can be determined.

2. Application of Horner plot and assumption of cylindrical flow for the reservoir system described above are inadequate in providing reservoir parameters and could lead to serious errors. In particular, skin factors and permeability thickness products calculated from Horner plot are not reliable.

NOMENCLATURE

		<u>Oil Field Unit</u>	<u>Metric</u>
B	= Fluid formation volume factor	dimensionless	dimensionless
$\phi_1 C_1$	= Fluid capacitance of the matrix	psi ⁻¹	(kg/cm ²) ⁻¹
$\phi_2 C_2$	= Fluid capacitance of the fracture network	psi ⁻¹	(kg/cm ²) ⁻¹
h	= Formation thickness	ft	m
h _c	= Completion thickness	ft	m
k ₁	= Permeability of the matrix	md	darcy
$\bar{k}_2$	= Effective permeability of the porous medium	md	darcy
m	= Slope of the pressure buildup curve	psi - $\sqrt{\text{min.}}$	(kg/cm ²) - $\sqrt{\text{hr.}}$
P*	= Pressure corresponding to infinite closed in time in an infinite reservoir	psi	kg/cm ²
P _{wf}	= Wellbore flowing pressure	psi	kg/cm ²
ΔP^*	= P* - P _{wf}	psi	kg/cm ²
ΔP^2	= P* ² - P _{wf} ²	psi ²	(kg/cm ²) ²
P _{ws}	= Wellbore shutin pressure	psi	kg/cm ²
q	= Production rate	Bbl/D	ton/hr.
r _w	= Wellbore radius	ft	m
r _{ew}	= Equivalent wellbore radius	ft	m
s	= Laplace Transformation Variable	dimensionless	dimensionless
S	= Skin factor	dimensionless	dimensionless
t	= Producing time before shut-in	min.	hrs.
Δt	= Shutin time	min.	hrs.
t _D	= Dimensionless time	$\frac{4.4 \times 10^{-6} \bar{k}_2 t}{(\phi_2 C_2 + \phi_1 C_1) \mu r_{ew}^2}$	$\frac{.3604 \bar{k}_2 t}{(\phi_2 C_2 + \phi_1 C_1) \mu r_{ew}^2}$

		<u>Oil Field Unit</u>	<u>Metric</u>
T	= Temperature	$^{\circ}\text{R}$	$^{\circ}\text{K}$
P_D	= Dimensionless pressure drop	$\frac{P_i - P}{k_2 \cdot r_{ew}}$	$\frac{P_i^2 - P^2}{k_2 \cdot r_{ew}}$
μ	= Fluid viscosity	cp	cp
ϕ	= Porosity	fraction	fraction
ω	= $\frac{\phi_2 C_2}{\phi_2 C_2 + \phi_1 C_1}$	fraction	fraction
λ	= $\alpha \frac{k_1}{k_2} \cdot r_{ew}$ interposity flow coefficient	dimensionless	dimensionless
α	= Geometric parameter	$1/\text{ft.}^2$	$1/\text{m}^2$
σ	= $s \cdot \omega$		
v	= $\omega/(1 - \omega)$		
τ	= t_D/ω		
() _a	= Assumed		
() _c	= Computed		
() _M	= Match point		

Mathematical Symbol

$\text{erfc}(\chi)$ = Complimentary error function

$$= \frac{2}{\sqrt{\pi}} \int_{\chi}^{\infty} e^{-u^2} du$$

$\mathcal{L}^{-1}$ = Inverse of Laplace Transformation

Acknowledgments

Several graduate students and faculty members at the Department of Petroleum Engineering, University of Southern California, contributed to fulfillment of this study. Their help was made possible through the financial support of State Lands Division. The Author wishes to acknowledge the assistance and continued support of Messrs. D. J. Everitts and C. F. Eaton during the course of this investigation.

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TABLE 1

DIMENSIONLESS PRESSURE DROP AS A FUNCTION OF DIMENSIONLESS
TIME AS INFLUENCED BY THE VALUE OF " λ "

$$\omega = 0.1$$

t_D	P_D			
	$\lambda = 0.0001$	$\lambda = 0.00001$	$\lambda = 0.000001$	$\lambda = 0.0000001$
0.0001	0.03471	0.03471	0.03471	0.03471
0.001	0.10354	0.10354	0.10354	0.10354
0.01	0.27642	0.27642	0.27642	0.27642
0.1	0.57240	0.57241	0.57242	0.57242
1.0	0.84932	0.82941	0.82942	0.82942
10.0	0.94339	0.94381	0.94385	0.94386
100.0	0.98052	0.98200	0.98215	0.98217

TABLE 2
SUMMARY OF CALCULATION

<u>ITEM</u>	<u>FIRST TRIAL</u>	<u>SECOND TRIAL</u>	<u>THIRD TRIAL</u>
$(\phi_2 C_2 + \phi_1 C_1), (k_g / \text{cm}^2)^{-1}$	0.002	0.005	0.009
$(\bar{k}_2)_a$	0.020	0.0277	0.0337
ΔP^*	2053	1482.7	1218.7
$(t_D)_M$ for $\Delta t = 10$ hrs	.569	.315	.213
w	> 1	> 1	0.7
$(P_D)_M$ for $t = 10$ hrs			.42
$(\bar{k}_2)_c$			.0335

Fig. 1 Spherical Flow

Fig. 2 Dimensionless Pressure Drop versus Dimensionless Time For Different Values of " ω ".

Fig. 3 Horner Plot of the Steam Well Buildup Data
Used in Example (after Ramey and Gringarten⁸)

Fig. 4 Type Curve Plot of the Steam Well Buildup
Used in Example (after Ramey and Gringarten⁸)

Fig. 5 Pressure Buildup Data for the Steam Well in Example Assuming Spherical Flow

Fig. 6 Type Curve Matching for the Steam Well