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EMPHASIZING SUBMERGED ENVIRONMENTS

Charles W. Case and Pat Wilde

May 21, 1976

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METHODS FOR GEOTHERMAL RESERVOIR DETECTION
EMPHASIZING SUBMERGED ENVIRONMENTS

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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 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.	Analyses 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 temperature 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 effect 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 - measureable 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 affect 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 continually monitoring reservoir activity.

1

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 content 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 ⁻¹	232	18,166	16,668	126,430	69	1187	1639	55	48	571	1,390	1870	11,200	12,040	53	6,296
SO ₄ ⁻²	4,139	<10	21.8	7,530	8.5	4,960	257	2.0	1.0	135	264	1.6	307	576	1.2	103,680
F ⁻¹	1.6			23	.2	4.9	4.8	.1	.1			7.0	10	6.0		
Cl ⁻¹	9,033	905	5,945	15,100	1.0	21,400	109	3.5	2.2	1,725	1,960	22	1,160	3,330	1.2	1,668
NO ₃ ⁻¹	1.2			2.4	.2		.50	.1	0			1.6	2.2	.4	.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	7.5	640
Mg ⁺²	581	24	30.7	32	2.5	148	.2	3.2	2.7	18	113	49	.9	8.9	2.9	22,838
Sr ⁺²		5.3		96			.24									
Li ⁺¹	1.9	1.2		8.5			.16									
Na ⁺¹	6,249	3,390	6,199	21,400	9.2	14,100	423	6.1	4.3	1,321	1,630	220	1,370	3,180	6.5	7,337
K ⁺¹	112	731	332	1,120	2.3	594	17.1	1.6	1.4	70	134	59	11	7.5	2.1	891
B.....	5.0	360	221	157	.10	60	.84	.00	.00			.03	19	38		
Fe.....				.21				.00	.03			.00	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 (1955a).
- 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 (1955a).
- I. Truckee River at Farad, Calif. Collected Sept. 22, 1953. U.S. Geol. Survey (1955a).
- J. Winnemucca Lake, Nev. Clarke (1924b, p. 160).
- K. Pyramid Lake at Sutcliffe, Nev. Collected Sept. 19, 1955. 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. 22, 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 ⁻¹	42	107	256	179	235	163	183	79	62
SO ₄ ⁻²	5.2	101	794	230	231	256	289	11	5.2
F ⁻¹	.3			.3	.3	.3	.2	.4	.0
Cl ⁻¹	1.1	38	24	49	70	75	113	7.1	4.0
NO ₃ ⁻¹	0.8	1.3	2.0	2.2	1.9	1.4	1.0	.6	.0
Ca ⁺²	9.6	55	148	75	91	84	94	12.9	14
Mg ⁺²	1.9	11	81	28	28	27	30	7.0	2.7
Na ⁺¹	3.8	26	166	70	80	88	124	10.5	7.7
K ⁺¹	2.7	3.5	6.1	4.0	5.8	2.9	4.4	1.3	.9
B.....	.00	.00					.052	.10	.010
Fe.....	.14	.06	.06	.03	.09	.05	.01	.08	.112
Al.....							.012	.06	0.60
SiO ₂	9.3	7.4	9.9	12	14	13	14	19	20
Total dissolved solids.....	76.8	351	1,490	650	757	711	853	149	117

- A. Colorado River at Hot Sulfur 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 [1955]).
- E. Colorado River near Grand Canyon, Ariz. Oct. 1949 to Sept. 1950. U.S. Geol. Survey (1954d [1955]).
- F. Yuma main canal below Colorado River siphon at Yuma, Ariz. Oct. 1949 to Sept. 1950. U.S. Geol. Survey (1954d [1955]).
- G. Colorado River at bridge on U.S. Highway 80 at Yuma, Ariz. Sept. 16, 1958. Durum, Heidel, and Tison (1960). Analysis includes AG, 0.0010 ppm; Ba, 0.152 ppm; Co, 0.000 ppm; Cr, 0.024 ppm; Cu, 0.0088 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; Ti, <0.0080 ppm; and Zr, 0.000 ppm.
- H. Sacramento River at Rio Vista, Calif., 1956. 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, <0.000086 ppm; Ba, 0.031 ppm; Co, 0.000 ppm; Cr, 0.0044 ppm; Cu, 0.0029 ppm; Li, 0.0021 ppm; Mn, 0.0063 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; Ti, <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	1) gravimetric
2) Na/K	2) volumetric
3) Na/Ca	3) colorimetric
4) Mg/Ca	4) X ray emission
5) Cl	5) flame emission
6) Cl/F	6) polarography
7) Cl/B	7) neutron activation
8) Ca and HCO_3	8) emission spectroscopy
9) S	
B. <u>Analysis of Gas:</u>	
1) H_2S	1) volumetric
2) CO_2	2) emission spectroscopy
3) NH_3	3) absorption spectroscopy
4) various ratios	4) mass spectroscopy
	5) gas chromatography
C. <u>Analysis of Deposits:</u>	
1) Hg	1) gravimetric
2) SiO_2	2) volumetric
3) CaCO_3	3) field methods
4) radioactivity	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	1) same techniques as water analysis
2) pH analysis	
3) rate of discharge	

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 ^a 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.

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

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

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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