*Heat Flow and Hot Dry Rock Geothermal
Resources of the Clearlake Region,
Northern California*

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*Heat Flow and Hot Dry Rock Geothermal
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TABLE OF CONTENTS

LIST OF TABLES	vi
LIST OF FIGURES	vi
ABSTRACT	1
I. INTRODUCTION.....	1
A. HDR technology	1
B. Units	3
C. Nomenclature	3
II. SURFACE HEAT FLOW.....	3
A. The Geysers-Clear Lake Geothermal Anomaly	3
B. Thermal Conductivity	4
C. Temperature Gradients from Deep Wells	4
D. Conductive Heat Flow Regime	8
E. Temperature Gradients from Shallow Wells:.....	9
F. Statistically Different Regions.....	10
G. Generalized Map of Heat Flow	11
III. MAGMATECTONICS OF NORTHERN CALIFORNIA	13
A. Introduction	13
B. Plate Tectonics of the NE Pacific	13
C. Migration of Volcanism.....	15
D. Magmatic Processes.....	19
F. Asthenospheric Uplift	21
G. Magma Bodies at Clearlake	23
IV. GEOTHERMAL RESOURCES.....	27
A. Introduction	27
B. Resource Base, Resources and Reserves.....	27
C. Resource Terminology.....	28
D. Revised Resource Terminology.....	28
E. HDR Resources.....	29
F. HDR Reserves	30
V. PREVIOUS ESTIMATES OF HDR RESOURCES AT CLEARLAKE.....	30
A. Igneous-related Geothermal Resources	30
B. Igneous-related HDR Resources.....	31
VI. HDR RESOURCES OF THE CLEARLAKE REGION.....	31
A. Temperatures in Depth.....	31
B. Discretized Heat Flow.....	32
C. Boundaries of the HDR Resource Area.....	32
D. Calculation of Resources	33
E. Electric Power Potential.....	34
VII. SUMMARY.....	35
ACKNOWLEDGMENTS.....	36
REFERENCES.....	37

LIST OF TABLES

Table 1: Thermal conductivities of rocks onshore in The Geysers-Clear Lake area...	4
Table 2: Geothermal gradients and heat flow in deep wells in the Clearlake region.....	7
Table 3: Statistical summaries of heat flow in various regions of The Geysers-Clear Lake geothermal anomaly.....	10
Table 4: Mineral geothermometers for the Clear Lake Volcanics.....	24
Table 5: Hierarchy of geothermal resource categories.....	28
Table 6: Simplified geothermal and HDR resource categories.....	29
Table 7: Estimated heat content of the volcanic system near Clearlake and for comparison, and some other selected Californian igneous systems.....	31
Table 8: Geothermal resources of the Clearlake region.....	34
Table 9: Efficiencies of power production from various categories of geothermal resources.....	35

LIST OF FIGURES

Figure 1: Locality map of northern California.....	2
Figure 2: Map of the location of deep wells in the Clearlake region.....	5
Figure 3: Temperature versus depth for five deep wells in the Clearlake region.....	6
Figure 4: Temperatures in depth approximately along the northeast-trending axis of the geothermal anomaly.....	9
Figure 5: Temperature gradients and heat flow for shallow wells north of Clearlake.....	10
Figure 6: Sketch map of heat flow in The Geysers-Clear Lake area.....	12
Figure 7: Tectonics of western North America.....	14
Figure 8: Restored map of northern California showing ages of volcanics.....	16
Figure 9: Ages of volcanic complexes plotted against the distance, adjusted for faulting, from the present position of the Mendocino triple junction.....	17
Figure 10: Distribution of young volcanic rocks in the Clear Lake area.....	18
Figure 11: Longitudinal (north-south) cross section of the Pacific-North American plate margin.....	20
Figure 12: Lithospheric configuration and fault zone evolution after passage of the Mendocino triple point.....	21
Figure 13: Temperature structure of the lithosphere following passage of the Mendocino triple junction.....	22
Figure 14: Hypothetical cross section through the magma system underlying the Mt. Konocti area at a late stage of development.....	25
Figure 15: Schematic cross section of The Geysers-Clear Lake area based upon a reconciliation of petrogenic and geophysical data.....	27
Figure 16: Diagram of heat flow versus cumulative area for The Geysers-Clear Lake area.....	32

HEAT FLOW AND HOT DRY ROCK GEOTHERMAL RESOURCES OF THE CLEARLAKE REGION, NORTHERN CALIFORNIA

by

Kerry L. Burns

ABSTRACT

The Geysers-Clear Lake geothermal anomaly is an area of high heat flow in northern California. The anomaly is caused by abnormally high heat flows generated by asthenospheric uplift and basaltic magmatic underplating at a slabless window created by passage of the Mendocino Triple Junction.

The Clear Lake volcanic field is underlain by magmatic igneous bodies in the form of a stack of sill-form intrusions with silicic bodies generally at the top and basic magmas at the bottom. The tabular shape and wide areal extent of the heat sources results in linear temperature gradients and near-horizontal isotherms in a broad region at the center of the geothermal anomaly.

The Hot Dry Rock (HDR) portion of The Geysers-Clear Lake geothermal field is that part of the geothermal anomaly that is external to the steamfield, bounded by geothermal gradients of 167 mW/m² (4 heat flow units—hfu) and 335 mW/m² (8 hfu). The HDR resources, to a depth of 5 km, were estimated by piece-wise linear summation based on a sketch map of the heat flow. Approximately, the geothermal "accessible resource base" (Q_a) is 1.68E+21 J; the "HDR resource base" (Q_{ha}) is 1.39E+21 J; and the "HDR power production resource" (Q_{hp}) is 1.01E+21 J. The HDR power production resource (Q_{hp}) is equivalent to 2.78E+11 Mwht (megawatt hours thermal), or 1.72E+11 bbls of oil.

I. INTRODUCTION

A. HDR Technology

The most productive source of geothermal electric power has been dry steamfields, such as at The Geysers in northern California. Surrounding these steamfields are areas of hot rock which are devoid of fluid. The HDR production method aims to exploit this surrounding resource by introducing a working fluid from external sources.

HDR technology has been under development by Los Alamos National Laboratory at Fenton Hill, in the Jemez Mountains of New Mexico, for about 20 years. At present power is being produced at a rate of about 4 Mwht (megawatts thermal) from an artificial reservoir in Precambrian granite gneiss. The depth range is 3.35 to 3.66 km (10 900 to 12 000 ft), and the temperature range at those depths is 231 to 243°C (445 to 469°F). The method entails 100% reinjection of working fluid and operations at pressures up to 27.6 MPa (4000 psi) above hydrostatic.

The Clearlake HDR project examines the feasibility of operating an HDR plant in northern California. The aim is to determine the generic site requirements for such a plant, and to determine whether The Geysers-Clear Lake area meets those requirements. The area

of most interest is the northeast extremity of The Geysers-Clear Lake known geothermal resource area, northeast of the Highlands arm of Clear Lake (Figure 1).

Figure 1: Locality map of northern California. The shaded areas are geothermal anomalies, with heat flow higher than 167 mW/m^2 (4 hfu), after Higgins (1980). The largest anomaly is The Geysers-Clear Lake area, with The Geysers steamfield shown blank. The smaller regions are the Napa Valley (NP-CA), the Sonoma Valley (SO), and Wilbur Hot Springs (WHS). Portions of counties shown on the map are Colusa, Lake, Marin, Mendocino, Napa, Solano, Sonoma, and Yolo. Mount St. Helena (MSH) is a prominent peak in the Sonoma Volcanics. Townships are CA, Calistoga; CD, Cloverdale; GS, Geyserville; HD, Healdsburg; HP, Hopland; LP, Lakeport; MD, Middletown; NP, Napa; SO, Sonoma; SR, Santa Rosa; UK, Ukiah; and WHS, Wilbur Hot Springs.

B. Units

This report uses SI metric units throughout (International System of Units), based on the report (SPE, 1977) of the Metrication Subcommittee of the Society of Petroleum Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc. (SPE of AIME). Some mathematical expressions herein are given in Iverson notation. The usage is explained in Section IV. D, where the expressions are introduced.

Some data used in this report were converted from original sources using conversion factors as follows. 1 ft (U.S. survey foot) = 0.304 800 6 m; 1 cal = 4.184 J; 1 Btu (British thermal unit, International) = 1.055 056 E+3 J; 1 hfu (heat flow unit, ucal/s.cm²) = 41.84 mW/m²; 1 hgu (heat generation unit, 1E-13 cal/s.cm³) = 0.418 4 uW/m³; 1 tcu (thermal conductivity unit, mcal/s.cm.°C) = 0.418 4 W/m.K, and 1 quad = 1.0 E+15 Btu; 1 psi (lbf/in²) = 6.894 757 E-3 MPa, and the disused unit, 1 Q = 1000 quads.

The thermal conductivity (*L*) of the bulk rock in situ is taken to be 2.97 W/m.K (7.1 tcu) (Walters and Combs, 1989, Tab. 2 p. 495; 1992, Tab. 2 p. 47), and the volumetric heat capacity of the rock (*C*) to be 2.72E+6 J/m³.K (0.65 cal/cm³ °C) (Hot Dry Rock Assessment Panel—HDRAP 1997).

C. Nomenclature

We use the nautical cardinal points, quarter and eighth points to specify direction, thus the points in the first quadrant are N, NNE, NE, ENE, and E. Where this is insufficiently precise, we use the aeronautical azimuth, expressed in the form N30°E, meaning 30 degrees east of north.

References to "Figure" and "Table" refer to illustrations in this report. References to "Fig. " and "Tab. " refer to citations in external documents.

Clear Lake has a large circular basin at the north end, and two arms. The eastern is Oaks Arm, and on the north shore is the township of Clearlake Oaks. The southeastern is Highlands Arm, and on the northeastern shore was the township of Clearlake Highlands, which became incorporated as the City of Clearlake. The name "Clear Lake" applies to the lake and to the volcanic field on its western side. The name "Clearlake" is used for the city and its surrounding region.

John C. Fremont's expedition of 1847 discovered geothermal manifestations in northern California and named the locality "The Geysers." This form, with the capitalized definite article, has become traditional and is widely used in the geothermal literature (e.g., Koenig 1992). In 1957 drilling discovered a steamfield at a depth known as "The Geysers steamfield." The area of high heat flow, which includes The Geysers steamfield and extends in the northeast direction beyond Clear Lake, is known as "The Geysers-Clear Lake geothermal field." The administrative district that includes and surrounds The Geysers-Clear Lake geothermal field is named "The Geysers-Clear Lake Known Geothermal Resource Area," or "The Geysers-Clear Lake KGRA" (Koenig 1992, Fig. 1, p. 8).

II. SURFACE HEAT FLOW

A. The Geysers-Clear Lake Geothermal Anomaly

There is a region of high heat flow in the northern California Coast ranges, constituting The Geysers-Clear Lake geothermal anomaly, with boundaries as shown in the locality map (Figure 1). The steamfield at The Geysers is the region of highest heat flow;

this occurs on the western margin of the geothermal anomaly and is elongated in the northwest direction. The "Clearlake region" is here defined as an area of high heat flow without steamfields extending to the northeast of The Geysers steamfield, across the Clear Lake volcanic field to Clear Lake at Highlands Arm, and then across Highlands Arm to beyond the city of Clearlake. The Clearlake region is the proposed Hot Dry Rock resource region.

B. Thermal Conductivity

Thomas (1986) published mean values of thermal conductivity measured on 55 to 64 specimens of three different rock types. Walters and Combs (1989, 1992) assembled data on thermal conductivities of rocks in this region. In many cases, the measurements were made on cuttings from corporate archives. The results are summarized in Table 1.

Lithology	Source*	No. of specimens	Range low	Range high	Mean	Standard deviation
Clear Lake volcanics (Quaternary)						
Olivine basalt	2	12	1.42	2.18	1.72	0.19
Dacite	2	27	1.21	2.14	1.68	0.25
Andesite	2	6	1.59	1.80	1.68	0.07
Rhyolite	2	23	0.75	1.80	1.09	0.23
Great Valley sequence (Jurassic-Cretaceous)						
Sandstone	2	59	2.21	3.30	2.68	0.21
Shale	2	35	1.92	2.68	2.22	0.17
Ophiolite (Jurassic)						
Serpentinite	1	---	----	----	2.39	---
Serpentinite	2	85	1.84	3.43	2.64	0.36
Franciscan assemblage (Jurassic-Cretaceous)						
Greenstone	1	---	----		2.42	----
Greenstone	2	73	1.88	3.14	2.47	0.33
Graywacke	1	---	----	-----	3.22	----
Graywacke	2	563	2.43	3.77	2.97	0.29
Chert	2	21	3.02	4.15	3.56	0.29

Table 1: Thermal conductivities of rocks onshore in The Geysers-Clear Lake area.

*Sources are (1) Thomas (1986, Fig. 4) and (2) Walters and Combs (1989 Tab. 2 and 1992 Tab. 2).

C. Temperature Gradients from Deep Wells

The geothermal anomaly attracted a series of deep wells from private geothermal exploration companies. The locations of some important ones in the Clear Lake area are shown in Figure 2. Examples of temperature profiles derived from wireline logs are shown in Figure 3.

Figure 2. Map of the location of deep wells in the Clearlake region. From Burns and Potter (1990, Fig. 3) and Urban and Diment (1988, Fig. 2).

Figure 3. Temperature versus depth for five deep wells in the Clearlake region. The heavy line included for comparison, is the straight line through 15.6°C at zero depth with gradient of 100°C/km. From Burns and Potter (1990, Fig. 4).

The geothermal gradient (G) is the partial derivative of temperature with true vertical depth (Jaeger, 1965). Gradients may be measured from bottom hole temperatures when drilling into undisturbed rock, using the difference between a stable bottom hole temperature and the average mean surface temperature, as described by Walters and Combs (1989, 1992). If the bottom hole temperature is declining exponentially, the equilibrium value may be found by the method of Albright (1975).

Geothermal gradients may also be determined from wireline logs. An interval is selected in the log in which the relationship of temperature versus depth appears to be linear, corresponding to the physical situation of uniform heat flow through a material of constant conductivity. The linear regression of temperature versus depth has the form $T = T_0 + G \cdot z$, where T is the temperature at depth z . The goodness-of-fit of the computed line to the data points may be measured by R^2 , the ratio (sum of squares of residuals)/(total sum of squares), as in Davis (1973, p. 197). T_0 is the intercept on the temperature ordinate of the regression line projected back to the surface.

The thermal conductivity (L) is measured on drillers' samples, if available, or estimated in proportion to lithology, from a table of conductivities for various lithologies, such as Table 1 above. It is then adjusted for porosity and temperature of the rock *in situ*, as described by Williams et al. (1993). The heat flow (H) is then calculated from $H = G \cdot L$. Table 2 is a collection of published results.

Name of Well		Location (T,R,S)	Completion date	Depth	Measuring date	Interval low	Interval high	No. of data	Inter- cept	Tempera- ture gradient (G)	Goodness of fit (R2)	Thermal conduc- tivity (L)	Heat flow	
	Note	(N W #)	(y m d)	(m)	(y m d)	(m)	(m)	(#)	(K)	(mK /m)		(W/ m.K)	(mW /m2)	(hfu)
130709-1	3a	13 07 09	79 08 07	502	79 08 07	0	496	73	25.8	16.0	0.9329			
Audrey A-1	2h	13 07 08		1897						138		2.72	375	9.0
Audrey A-1	3ah	13 07 08	81 02 09	3061	81 04 08	61	1128	286	16.0	142	0.9942	2.72	385	9.2
Borax Lake 7-1	2	13 07 07		2414						94.2		2.72	256	6.1
Borax Lake 7-1	3a	13 07 07	78 04 24	2414	78 05 31	6	2412	396	15.1	88.4	0.9921	2.72	240	5.7
Borax Lake 7-1	3a	13 07 07	78 04 24	2414	78 08 23	244	2412	357	2.7	96.0	0.9937	2.72	261	6.2
Bouscal 1-2	2	12 07 30		2412						94.7		2.60	246	5.9
Bradley #1	1h	13 07 05		643						323.5				
Bradley MC-1	3m	13 07 05	64 06 14	637	64 06 12	61	488	17	45.6	322.6	0.9633	2.80	903	21.6
Bradley #2	1h	13 07 05		1226						133.0				
Bradley MC-2	3ah	13 07 05	64 07 28	1215	64 07 25	30	762	10	11.8	136.7	0.9885	2.80	383	9.1
Clear Lake #1	1h	13 07 05		460						293.5				
Hannah Strat-2	3a	12 09 01	79 08 03	611	79 08 27	30	574	90	14.0	109.7	0.9941	2.64	290	6.9
Jorgensen 1	2	13 08 36		3139						86.8		2.47	214	5.1
Jorgensen-1	3m	13 08 36	81 02 14	3219	78 12 06	1829	2134	5	8.7	86.2	0.9992	2.47	213	5.1
Kettenhofen #1	1	13 08 33		109.9						110.0				
Magma-Watson #1	1	13 08 20		1755						>114.				
Neasham #1	1h	12 08 08		3015						>86.2				
Neasham 1	2	12 08 08		2756						85.4		2.72	232	5.6
Sullivan #1	1	12 08 18		1970						98.0				
Sulphur Bank #1	1h	13 07 05		168						>595				
Torchio-Ferro #1	1	12 10 24		2445						51.5				

Table 2: Geothermal gradients and heat flow in deep wells in the Clearlake region. Caption continues next page.

Table 2: Geothermal gradients and heat flow in deep wells in the Clearlake region. Sources noted in column 2 are Heiken et al. (1982, Tab. III p. 19), Goff and Decker (1982 Tab. III and 1983 Tab. III), and Walters and Combs (1989 Tab. 3 and 1992 Tab. 3). Depth is the total depth of the well at the time of measurement. Factors affecting the quality of observations are denoted by suffixes *a*, *m*, and *h* in column 2, explained in the text.

The estimation of heat flow from drilling records, which are usually incomplete, is subject to considerable error. The suffixes *a*, *m*, and *h* in Table 2 are a qualitative indication of possible error.

Transient disturbances are caused by drilling and testing. They take weeks or months to die away. Some logs were run before the wells were fully recovered. Estimates made from logs run at these times are denoted *m*. The geothermal gradient cited in Table 2 could be in error by as much as about 30% of the true value.

The wireline logs were disturbed by short-range structural and hydraulic features, such as convective circulation associated with hydraulically active fractures and aquifers. The goodness-of-fit measure in Table 2 indicates whether the curve of temperature versus depth is a good approximation to a straight line. If the temperature distribution in the well was stable, and the regression line is close to linear, the measurement quality is denoted *a* in Table 2. The geothermal gradient could be in error as much as about 10% of the true value.

The temperature distributions found in some deep wells were not representative of the broad, regional conductive heat flow, but were affected by nearby convective hydrothermal systems. These measurements are denoted by *h* in Table 2. For example, the high geothermal gradients and heat flows in the Audrey, Bradley, Clear Lake and Sulphur Bank wells are thought to be affected by their proximity to Sulphur Bank Mine Hot Spring.

Because the well records are subject to differing interpretations, agreement between different authors and different methods is an important means of verifying the results. The table shows good agreement on geothermal gradients between different sources for the wells Audrey, Borax Lake, Bradley 1 and 2, Jorgensen, and Neasham. The differences do not exceed 3%.

D. Conductive Heat Flow Regime

The Clearlake region is a conductive heat flow regime, as demonstrated by the linear temperature gradients in deep wells, some examples of which were shown in Figure 3. The observed temperature gradients range from 86 to 92 mK/m, and are sensibly linear down to depths of about 3.5 km.

The isotherms in depth along the northeast heat flow axis are shown in the temperature profile of Figure 4. This is a cross section showing the position of the 300°C isotherm in depth. Except in the vicinity of the hot spring at the northeastern (right-hand) end of the section, the isotherm is fairly level, implying that heat flow vectors tend to be vertical and subparallel and that the Franciscan basement is acting like a thick conductive "flux plate."

Figure 4: Temperatures in depth approximately along the northeast-trending axis of the geothermal anomaly. Note that the depth scale is based on sea level. From Burns et al. (1992, Fig. 4).

E. Temperature Gradients from Shallow Wells

Shallow exploration wells, or “temperature gradient holes,” were drilled by various explorers. Temperature and heat flow measurements for shallow wells were issued for The Geysers region by Urban et al. (1975) and by Thomas (1986), for offshore in Clear Lake by Urban and Diment (1988), and for the margins of The Geysers-Clear Lake geothermal anomaly by Walters and Combs (1989, 1992). For this report, preliminary examinations were made of another 167 shallow wells near Clearlake.

Examples of measurements in shallow wells are shown in Figure 5. This figure shows graphs of temperature versus depth for a series of shallow wells located northeast of the city of Clearlake. The geothermal gradients for these examples range from 78 to 112 mK/m. Using thermal conductivities from Thomas (1985), the heat flow ranges from 257 to 322 mW/m² (6.1 to 7.7 hfu).

Figure 5: Temperature gradients and heat flow for shallow wells north of Clearlake.

F. Statistically Different Regions

Statistical summaries of heat flow measured in various regions of the geothermal anomaly are shown in Table 3. The measurements were made in different regions, which is reflected by differences in the mean values. The average heat flow for The Geysers steamfield is 322 W/m² (7.7 hfu); for the Clearlake region is 238 mW/m² (5.7 hfu); for the margins of the geothermal anomaly is 184 mW/m² (4.4 hfu), and for the offshore region of Clear Lake 67 mW/m² (1.6 hfu).

Region	No of Data	Minimum	Maximum	Arithmetic Mean	Standard Deviation
		hfu	hfu	hfu	hfu
Steamfield	124	1.4	46.3	7.7	5.1
Clearlake	87	1.5	16.4	5.7	2.9
Margin	67	3.1	6.1	4.4	0.7
Offshore	7	1.2	2.4	1.6	0.4

Table 3: Statistical summaries of heat flow in various regions of The Geysers-Clear Lake geothermal anomaly. Data for the Clearlake region are preliminary. Data for The Geysers steamfield are from Thomas (1986, Tab. 1); data for the margin of the geothermal anomaly are from Walters and Combs (1989, Tab. 3 and 1992, Tab. 3); data for the Clearlake Region are from Burns et al. (1995, Tab. 1, p. 262e with an error corrected); and data for the region offshore in Clear Lake are from Urban and Diment (1988, Tab. 1 and Tab. 2).

G. Generalized Map of Heat Flow

Figure 6 is a sketch map of the heat flow in The Geysers-Clear Lake geothermal anomaly based upon data available in March 1993. This is a generalized sketch map which aims to represent the background conductive heat flow, and is drawn so as to smooth out small irregularities caused by localized hydrothermal features. The anomaly contains three heat flow "trends," which are the elongated high at The Geysers steamfield, with trend N305°E, and the low along Highlands arm, with trend N310°E. These directions have tectonic significance, as described in an accompanying report (Burns, 1996).

The heat flow contours shown in the vicinity of The Geysers steamfield are derived from Thomas (1986). The steamfield has a flat central high at about 502 mW/m² (12 hfu), and is elongated in the northwest direction. The axis of the high trends about N305°E.

The steamfield high declines steeply on its flanks to 335 mW/m² (8 hfu), where the rate of descent lessens. The steep decline enables us to separate the geothermal anomaly into two parts, The Geysers steamfield with a heat flow of 335 mW/m² (8 hfu) and larger, and a surrounding Clearlake anomaly.

The axis of high heat flow in the Clearlake region trends northeast, with an azimuth of N020°E. Along this axis, the heat flow drops off at the rate of 6.6 mW/m².km (0.16 hfu/km). The rate of decrease in the transverse direction is steeper, at about 10.7 mW/m².km (0.26 hfu/km). The outer contour at 167 mW/m² (4 hfu) is taken from Higgins (1980) and Walters and Combs (1989, 1992).

The region of low heat flow area along Highlands Arm of Clear Lake was discovered by Urban and Diment (1988). The cause is probably a graben structure, bounded on the south by the Konocti Bay Fault and on the north by the Main Basin Fault of Sims et al. (1988, Fig. 10). The low sketched along Highlands Arm on Figure 6 takes its direction (N310°E) from the graben. The width may be exaggerated on Figure 6. Resources under Highland Arm would be difficult to tap as a result of the problems of drilling through lake bottom sediments from an offshore platform, and they are not likely to be developed for the foreseeable future so that even if the low is not accurately portrayed, the resource exclusion zone is approximately as shown.

Figure 6: Sketch map of heat flow in The Geysers-Clear Lake area. Generalized from data in Thomas (1986), Urban and Diment (1988), Walters and Combs (1989, 1992), and Burns (1989). The line of cinder cones is after Burns (1992, Fig. 6).

III. MAGMATECTONICS OF NORTHERN CALIFORNIA

A. Introduction

The Geysers-Clear Lake area shows widespread manifestations of volcanic activity, including deposits of lava and tuff, cinder cones, and volcanic edifices such as Mts. Cobb, Hannah and Konocti. The heat flow is associated with young magmatism, and estimation of HDR resources requires an understanding of magmatic processes at depth.

Several different models have been offered for the magmatism at Clear Lake, including a migrating hot spot, leaky transform, asthenospheric upwelling, foundered subducting slab cut off the Farallon Plate (Isherwood, 1981), and finally, a slabless window related to the San Andreas fault system. This review presents the concept of the slabless window as the current consensus view.

B. Plate Tectonics of the NE Pacific

A plate tectonic model of the north-east Pacific region was assembled independently by McKenzie and Parker (1967) and Morgan (1968). A transform plate boundary first formed at the coastal trench off southern California. About 23.3 Ma, at the start of the Neogene, the San Andreas fault jumped onshore, and the present era of "neotectonics" commenced.

The San Andreas transform fault terminates at its northern end, off Cape Mendocino, in the Mendocino Triple Junction, an FFT (fault-fault-trench) junction in the classification of McKenzie and Morgan (1969). The fault terminates at its southern end, off the Gulf of California, in the Rivera Triple Junction, an RTF (ridge-trench-fault) junction (Figure 7).

Figure 7: Tectonics of western North America. Mercator projection. The northern (FFT) is the Mendocino triple point; the southern (RTF) is the Rivera triple point.

As the Pacific plate moves toward the North American plate, the two triple points migrate away from each other, “unzipping” the San Andreas fault. The Mendocino fracture zone first made contact with the North American continent somewhere near 30°N latitude. The Mendocino triple junction then migrated NNW to its present position off Cape Mendocino near 40°N latitude.

The Mendocino triple point has migrated north for the time periods 29 Ma to 21.2 Ma, 21.2 Ma to 10 Ma, 10 Ma to 4.5 Ma, and 4.5 Ma to 0 Ma, at the rate of 40 mm/a, 13 mm/a, 40 mm/a, and 55 mm/a, respectively (Atwater and Molnar, 1973). The total displacement is therefore 532.5 km in 15 Ma (35.5 mm/a), in the direction 325° E of N parallel to the San Andreas fault.

Transform jumps. Transform jumps were first postulated by Atwater (1970). These transfer slip from one fault to another. The second fault is parallel to the first and further inland. The result is not one single transform fault, but a transform system. The offset on the San Andreas fault, 314 km, is far less than the total offset on the San Andreas system, 500 km (Atwater, 1970; Dickinson and Snyder, 1979a; Fox et al. 1985).

C. Migration of Volcanism

The Clear Lake volcanics are merely the last of a series of volcanic complexes that extend from central to northern California, becoming younger to the north, as shown in Figure 8. The oldest complex in the sequence is the Pinnacles Volcanics, south of Holister, with an age of 23.5 Ma. Proceeding north, the ages get progressively younger. The Sonoma Volcanics associated with The Geysers steamfield are as young as 2.9 Ma. The northernmost complex is the Clear Lake volcanics, at 0.01 Ma to 2.1 Ma.

Analysis of the rate of volcanic migration is complicated by the effect of offsets on the transcurrent faults of the San Andreas system. Figure 8 is a "restored" map, which illustrates the location of the volcanic complexes with the offsets removed. The restoration follows Fox et al. (1985) and allows for slip of 115 km on the San Gregorio-Hosgri fault, 314 km on the San Andreas fault, 43 km on the Hayward-Rodgers Creek fault, and 28 km on Carneros-Franklin-Sunol-Calaveras fault.

In the restored map of Figure 8, the displacement from Page Mill to Clear Lake (PA-CL) is 248 km in 14.79 Ma in direction N 340° E, which is a migration rate of 17 mm/a. From a map constructed on similar principles by Hearn et al. (1981, Fig. 13), we estimate the migration rate at 14 mm/a, in reasonable agreement considering the difficulties of constructing restored maps. The displacement from Quien Sabe to Sutter Buttes (QU-SU) is 262 km in 9.55 Ma in direction N 347.5° E, which is a migration rate of 27 mm/a.

Figure 8: Restored map of northern California showing ages of volcanics. Four major occurrences are named: CL, Clear Lake; PA, Page Mill; SU, Sutter Buttes; QU, Quien Sabe. The centers of other volcanic fields are marked by filled dots with dates in Ma. Ages of volcanism are from various sources. The offshore traces are locations of the Mendocino Fracture Zone at dates from 3 to 15 Ma. The Mendocino triple point is off the map at 40.35° N latitude 124.75° W longitude. The migration paths QU-SU and PA-CL are conjectural.

However, it is difficult on these restored maps to represent the effect of changes of migration rate with time. Fox, Fleck, Curtis and Meyer (1985) prepared a diagram which shows a regional average migration rate of 37 mm/a for the period 25 to 12 Ma, and for northern California, a migration rate of 14 mm/a for the period from 12 Ma to the present (Figure 9).

Figure 9: Ages of volcanic complexes plotted against the distance, adjusted for faulting, from the present position of the Mendocino triple junction. The migration rates are AC, 32 mm/a; CD, 37.5 mm/a; AD, 35 mm/a; BC, 13.5 mm/a. Volcanic complexes are CL, Clear Lake Volcanics; SV, Sonoma Volcanics; TV, Tolay Volcanics; BH, volcanic rocks in the Berkeley Hills; PM, Page Mill Basalt; QS, Quien Sabe Volcanics; IB, Iverson Basalt; MB, Mindego Basalt; SC, basalt in the Felton-Santa Cruz area; TF, Tecuya Formation; NV, Neenach Volcanics; PV, Pinnacles Volcanic Formation; MR, Morro Rock-Island Hill complex; OF, Obispo Formation; TB, "Triple" basalt. From Fox, Fleck, Curtis and Meyer (1985, Fig. 4 p. 652).

Volcanism in northern California. Neogene magmatic activity north of San Francisco Bay began at about 12 Ma with the pyroxene-rich Tolay basalt-andesites (Johnson and O'Neil, 1984). Partial melting of the crust began with the Sonoma Volcanics at about 9 Ma to 11 Ma, with eruption of rhyolite and rhyodacite flows, and at 8 Ma, large volumes of andesite. At about 5 Ma, partial melting reached relatively shallow levels as evidenced by the oxygen geochemistry and the large volume of pyroclastic eruptions.

Between 2.7 Ma and 2.1 Ma the locus of magmatism shifted north to the Clear Lake area. Within the Clear Lake Volcanic complex, which was emplaced over the period 1.1 Ma to 0.01 Ma, Hearn et al. (1981) found evidence of steady northward migration in the distribution of radiometric ages within the field, as illustrated in Figure 10. From this figure, the rate of migration can be estimated at 18.6 km in 0.895 Ma, or 20.8 mm/a.

Figure 10: Distribution of young volcanic rocks in the Clear Lake area. The groups of radiometric ages are 0.8 Ma to 1.1 Ma, 0.3 Ma to 0.65 Ma, and 0.01 Ma to 0.1 Ma, respectively. The time sequence on this figure is from the bottom up. Symbols are **square** = rhyolite; **circle** = dacite; **triangle** = andesite; **x** = basaltic andesite; and **+** = basalt. From Hearn et al. (1981, Fig. 16, p. 33).

D. Magmatectonic Processes

Migrating hot spots. The parallelism and approximately similar timing of the displacements PA-CL and QU-SU on Figure 8 suggest that an explanation for the magmatism might be a system of migrating hot spots, as suggested for Cenozoic volcanism in Australia by Wellman and McDougall (1974). They found that the magmatism at any one location changed from intrusive dikes and plugs to central volcanics as a change from extensional to compressive stress swept across the continent from north to south.

There was a change in the northern Californian stress field from fault-normal extension to fault-normal compression at 4 Ma to 5 Ma (Zoback and Zoback, 1991), which is consistent with the appearance of central volcanics in the Clear Lake volcanic field.

In northern California, the change from basalt-andesites to rhyolites and rhyodacites at about 12 Ma to 10 Ma, the change from dikes and plugs to central volcanic complexes, and the change in the stress field at about 4 Ma to 5 Ma, occurs but once along the migration path. In Australia, the change occurs at all points along the migration path; that is, the change itself migrates. This indicates that while the tectonic processes have similarities, there are fundamental differences.

Propagating fault system. In central and northern California, the outbreak of local magmatism migrates north in concert with the onset of rapid Miocene sedimentation in terrestrial basins (Dickinson and Snyder, 1979a) and with the movement of the Mendocino triple junction (Fox et al., 1985). This indicates that volcanism is coupled to crustal deformation associated with neotectonic faulting.

The Mendocino Triple Point migrates in direction N325°E in northern California (the trend of the San Andreas fault) at a rate which has varied in time from 40 mm/a, to 13 mm/a, to 40 mm/a, to the present 55 mm/a.

From the restored map of Figure 8, we find that the volcanic rocks show a pattern of migration in the direction N340°E. From Figure 9 we estimate the rate of migration as 37 mm/a from 25 Ma to 12 Ma, and then 14 mm/a from 12 Ma to the present.

Therefore, the general direction and sense of travel are similar for both tectonic features. However the present rate of migration of the fracture zone, at 55 mm/a, is about four times as fast as the present rate of magma migration, estimated at 14 mm/a. It appears that the magmatic event is triggered by the fracture zone, but it then propagates at its own rate. The path of volcanic migration does not propagate parallel to the San Andreas fault but deviates inland from it by 15° (N340°E as compared to N325°E for the San Andreas fault).

Heat flow modeling by Furlong (1984) suggests that the appearance of the volcanics at the surface lags behind the passage of the triple junction by about one million years and that the eruptive duration for each volcanic complex is from 2 to 3 Ma.

Slabless window. Lachenbruch and Sass (1980) found that the heat flow rises for 200 km southwards from Cape Mendocino, reaching the anomalously high value of about 80 mW/m² (2 hfu), and maintaining that for 550 km further south. After consideration of various causes, including conductive heating from warm mantle below and frictional heating on the seismogenic layer of the San Andreas fault zone, they concluded that extreme mantle upwelling would be required to explain the heat flow and that asthenosphere conditions must apply at depths as shallow as about 20 km in the northernmost Coast Ranges. They spoke of a "buried one-sided spreading center migrating northward (with the Mendocino transform) as a 'hot line' beneath western North America."

These conclusions are in keeping with observations of the seismicity and lithospheric structure, topography and gravity field, and magnetic field, as reviewed by Burns et al. (1995). The geophysical observations permit the concept that the San Andreas transform is, at depth, a discontinuity in the structure of the lithosphere, with several processes proceeding simultaneously.

Relative to the North American plate, the slabless window can be viewed as the instantaneous disappearance of the subducting slab, creating a sublithospheric void. The void propagates northwards in pace with the triple junction. The appearance of the void is an impulsive change in the subsurface geometry, and the resultant deformation is a transient response to that. The asthenosphere feels the passage of the triple junction as a sudden removal of load (effectively, instantaneous lithospheric thinning, Furlong, 1984), to which it responds by uplift and decompression.

As the Gorda plate moves northward relative to the North American plate, asthenosphere ascends in a narrow channel adjacent to the south edge of the Gorda plate, accreting to the North American plate. Figure 11 attempts to portray the process.

Figure 11: Longitudinal (north-south) cross section of the Pacific-North American plate margin. Based on Lachenbruch and Sass (1980) and Zandt and Furlong (1982).

The slabless window supersedes earlier ideas of a potential gap in the subducting plate termed a "stable no-slab window" by Dickinson and Snyder (1979b), and an "unstable triple point" by Dickinson and Snyder (1979a) and Zandt (1981).

Tectonic setting of Clearlake. Furlong et al. (1989) modeled the thermo-mechanical evolution of the San Andreas transform fault zone in central and northern California and found the lithospheric configurations shown in Figure 12. The crust strengthens through underplating and cooling, then the transform jumps landward between (a) and (b), with a piece of lithosphere being transferred from the North American to the Pacific Plate, or "captured" by the Pacific Plate.

The Geysers steamfield and Collayomi fault are shown on the tectonic profile of Figure 12(c). The steamfield is placed above the slabless window.

Figure 12: Lithospheric configuration and fault zone evolution after passage of the Mendocino triple point. (a) is north of Cape Mendocino at 41°N latitude, (b) is immediately south of Cape Mendocino, (c) is through The Geysers-Clear Lake Geothermal area, (d) is near San Francisco Bay. Based on Furlong et al.(1989).

F. Asthenospheric Uplift

Diment et al. (1975, Tab. 13) assigned the "San Andreas fault zone" to a conduction-dominated basement regime with regional heat flow parameters similar to the Basin and Range, with a reduced heat flow of 1.4 hfu, and surface heat production of $2.1 \mu\text{W}/\text{m}^3$ (5 hgu) with a depth decrement of 10 km.

Lachenbruch and Sass (1980) found that the linear relationship between heat flow and heat production did not apply to the Central and Northern Coast Ranges. They found anomalously high heat flow values of about $80 \text{ mW}/\text{m}^2$ (2 hfu). They concluded that extreme mantle upwelling would be required to explain the heat flow, and that asthenosphere conditions must apply at depths as shallow as about 20 km in the northernmost Coast Ranges.

Furlong (1984) and Furlong et al. (1989) modeled the thermal evolution of the Coast Ranges using an exponential distribution of radioactive heat sources in depth, frictional heating on the fault zone, heat flow from a relatively warm mantle, and heat from cooling of asthenospheric material that rose to occupy the slabless window. The heat distribution at three different times after passage of the Mendocino Triple Point is shown in Figure 13.

Figure 13: Temperature structure of the lithosphere following passage of the Mendocino triple junction. Times after passage are, from top to bottom, 1 Ma, 5 Ma, and 10 Ma. Symbol SAF denotes the San Andreas fault. The right-hand scale is temperature in $^{\circ}\text{C}$. The initial extent of the emplaced asthenosphere is outlined by dashed lines. From Furlong et al. (1989, Fig. 4).

A consequence of the process is lithospheric underplating. One Ma after passage, the asthenosphere is raised by mantle upwelling to a depth of about 30 km (Figure 13, top). This material is approximately 200°C – 300°C above the local solidus and may contain up to 25% or 30% melt. The combined effects of convective heat transport and latent heat of crystallization in this melt will raise temperatures to between 700°C and 900°C . On solidification, this creates a basaltic “underplate” to the lithosphere.

Partial melting of the crust and associated volcanism follow. Maximum temperatures in the lower crust are reached in the first 2 Ma to 3 Ma after passage and remain within the crustal melting range for another 3 Ma to 5 Ma. The volcanism coincides in location with the region of reduced lithospheric strength. An interesting prediction is that outside the region of crustal melting, the heat pulse will be sufficient to metamorphose the crust to granulite grade. Granulitization is likely to be occurring at present.

G. Magma Bodies at Clearlake

Magmatic sources. The abundant evidence of surface volcanism and the very young ages indicate that the region near Clearlake is underlain at depth by molten rock. The magma bodies are fed from below and act as sources for the local heat flow.

Spherical magma chamber. Successively younger silicic volcanic centers occur at Cobb Mountain, Mt. Hannah, Mt. Konocti and Borax Lake (Stimac et al. 1992). Isherwood (1975, 1981) interpreted a negative gravity anomaly over Mt. Hanna as the result of a buried spherical magma chamber. Hearn et al. (1981) reviewed the relevant geophysical, thermal and petrographic evidence for the chamber. The possible subsurface configuration was shown in cross sections by Heiken et al. (1982, Fig. 8) and Goff and Decker (1982, Fig. 6). However the anomaly was rectangular in shape, and it overlays a NW-trending antiform in the Franciscan rocks. Blakely and Stanley (1993) confirmed, by two-dimensional modeling, that the anomaly was instead a result of shallow structures in the Franciscan rocks. Therefore, the notion of a single, large, spherical magma chamber under Mt. Hanna is no longer supported.

Geothermometry and geobarometry. The mineralogy and texture of lavas erupted at Clear Lake provide some constraints on the temperatures of their source magma bodies. Stimac has, as part of this study, examined several different mineral thermometers for this area. The results are shown in Table 4. A geothermometer based upon olivine-liquid thermometry gives a temperature of about 1000°C to 1150°C for basaltic andesite lavas. Two-pyroxene thermometry yields a temperature of about 900°C for crystal-poor rhyolites. Two-pyroxene and two-feldspar geothermometers give temperatures as low as 700°C for crystal-rich rhyolites. Dacitic magmas representing mixtures of rhyolitic and mafic magmas yield equilibrium temperatures of 800°C–900°C. The geobarometry is less definitive. All these thermometers are consistent with pressures of 2 kb, representing depths of approximately 6 km.

Volcanic rock unit	Two - pyroxene		Olivine	Two-feldspar
	(°C)		(°C)	(°C)
rhyolite RT of Thurston Creek	898	- 971		
rhyolite RT of Thurston Creek (<i>qmi</i>)	946	- 1082	1047-1065	
rhyolite RR of Red Hill Road				644- 671
rhyolite RR of Red Hill Road (<i>qmi</i>)			1020-1065	
basaltic andesites BK of Mt. Konocti			1115-1150	
basaltic andesite BM of McIntire Creek			996-1032	
	mafic	silicic		
dacite DSB of Mt. Konocti				736- 756
dacite DBR of Mt. Konocti	1078 (<i>ca</i>)	691- 697		
dacite DBR of Mt. Konocti	1084-1108 (<i>qmi</i>)			
dacite DKB of Mt. Konocti	919-1064 (<i>ca</i>)			736- 746
dacite DV of Thurston Lake	1010-1012 (<i>ca</i>)	651- 858		
dacite DT of Thurston Lake	923-1041 (<i>qmi</i>)			
crystal-rich rhyolites				696- 763

Table 4: Mineral geothermometers for the Clear Lake Volcanics. The dacites have two distinct mineral assemblages that equilibrated in mafic and silicic magmas. Equilibrium temperatures of mixed dacites are estimated to be in the range of 800°C to 900°C. Codes for texture are crystal aggregate (*ca*) and quenched mafic inclusion (*qmi*). The geothermometers are two-pyroxene, after Lindsley and Anderson (1993); olivine, after Roeder and Emslie (1970); and two-feldspar, after Fuhrman and Lindsley (1998). This table was adapted from Stimac et al. (1992, Tab. 1).

A two-level volcanic system. Stimac et al. (1990 and 1992), Stimac and Pearce (1992), and Stimac and Wark (1992) have remarked upon the implications of basaltic xenoliths in acidic rocks of the Clear Lake Volcanics. A well-known field manifestation is the mafic inclusions in rhyolite at the quarries opposite the school on Arrowhead Road in the City of Clearlake. The mineralogy, texture, chemistry and isotopic signature of the rhyolite of Borax Lake indicates it may represent a crustal melt superheated by interaction with more mafic magmas.

Establishment of a large silicic magma reservoir at Mt. Konocti was signaled by eruption of the rhyolite of Thurston Creek about 0.6 Ma and culminated with extrusion of mixed dacite from 0.4 Ma to 0.3 Ma. Textural and chemical evidence indicates that these dacites were formed by mixing of mafic magma with crystal-rich rhyolitic magma. A synthesis of petrologic and geophysical data by Stimac et al. (1992) gives the hypothetical cross section shown in Figure 14. The plutonic complex is inferred to comprise sheet-like to pod-like normally zoned granitic and granodioritic composite plutons underlain by dioritic to gabbroic rocks.

Figure 14: Hypothetical cross section through the magma system underlying the Mt. Konocti area at a late stage of development. Dacite is being generated by partial assimilation of silicic crystal mush by mafic magma. From Stimac et al. (1992, Fig. 4).

Two lines of evidence suggest that large-scale ponding of basaltic magma in the deep crust fostered high-grade metamorphism and partial melting of lower- to mid-crustal rocks. The first is the presence of xenoliths of high-grade metamorphic rocks in contaminated basaltic andesite and andesite lavas. The second is the isotopic and trace element geochemistry of silicic lavas, which reflect a large crustal component.

The differing density of silicic and mafic magmas in such a volcanic complex can lead to a situation where the silicic magma chambers effectively "block" the passage of mafic magmas to the surface. The effect is for a rising mafic magma to flow into the lower part of a silicic magma chamber, rather than rising through it. The result generates mixed magmas, such as dacites, at the base of the silicic chamber. The thermal effect is for the mafic magmas to keep the silicic magma chamber hot by periodic injections of heat. This explains the prolonged life of the Mt. Konocti system, and the duration of high heat flows for times in excess of the predictions of the conductive cooling models.

In accordance with this magmatic model, the young mafic volcanism NE of Clearlake (0.04 Ma to 0.01 Ma) may be a manifestation of basaltic dike injection at depth. The rhyolite flow at Arrowhead Road in the city of Clearlake is interpreted as the first silicic melt generated in a newly developing igneous complex.

Thus it may be inferred that there is a silicic magma under Arrowhead Road, at temperatures of about 650°C (see RR, Table 4), formed by melting of the crust at a depth of about 6 km. The heat causing the melting is supplied by high-temperature basaltic magmas at temperatures of about 1050°C (see BM, Table 4). The shape of the basaltic intrusions might be a northeast-trending magmatic ridge at great depth, marked by a line of cinder cones and andesite flows (see the eastern volcanic alignment, Figure 6).

Subsurface structure. Various geophysical methods have been used to try and determine the size and location of the various magma chambers at depth. They include gravity, magnetics, seismic source locations, seismic attenuation, seismic velocity reduction, and various electrical methods including magnetotellurics and time-domain electromagnetic sounding.

Stanley and Blakeley (1993) reviewed the geophysical data in the light of the petrogenic discoveries of Stimac et al. (1992). They found the geophysical data to be consistent with the petrogenic model, provided that no continuous magma zones occur shallower than 15 km depth, the high level felsic bodies are small and discontinuous, and silicic melt zones are thin and tabular (Figure 15).

Figure 15: Schematic cross section of The Geysers-Clear Lake area based upon a reconciliation of petrogenetic and geophysical data. Modified from Stanley and Blakely (1993, Fig. 6).

IV. GEOTHERMAL RESOURCES

A. Introduction

Following the Arab oil embargo of 1973, the US Geological Survey made two assessments of the geothermal resources of the United States. The first was by White and Williams (1975) in cooperation with the Energy Research and Development Administration. The second was made four years later by the United States Geological Survey (USGS) (Muffler 1979a), in cooperation with the Department of Energy. The electric power production potential of geothermal resources was addressed by EPRI (1978). Hot Dry Rock resources were defined and estimated by HDRAP (1977), and Heiken, Goff and Cremer (1982). The electric power production potential of HDR was treated by Tester et al. (1979).

B. Resource Base, Resources, and Reserves

The McKelvey diagram, developed by the USGS for mineral resource assessment, was applied by Muffler (1973), Muffler and Cataldi (1978, Fig. 3) and Muffler and Guffanti (1979, Fig. 2) to geothermal resources.

Muffler (1973) defined the "geothermal resource base," as the heat stored in rock at temperatures higher than the ambient temperature to a depth of 10 km. The ambient surface temperature is 15.6°C at Clearlake, and across the continental United States a commonly-

used value is 15°C. The maximum depth was set at 10 km for a continent-wide appraisal under conditions of national urgency. In recent years, the maximum depth is judged according to demonstrated achievements in drilling hard rock, and the costs are calculated against the realities of competition in the energy market. A depth of 5 km was favored in the recent survey of Australian continental resources by Somerville et al. (1994), while EPRI (1978) used a depth limit of 3 km.

The McKelvey diagram divided the resource base into categories depending upon degree of geological assurance and degree of economic feasibility. The geothermal "resource base" was the stored heat, both identified and undiscovered, that was recoverable using current or near-current technology, regardless of cost. The "geothermal reserves" was a small subset of the resource base that was demonstrated to exist and could be extracted profitably.

C. Resource Terminology

The most comprehensive discussion of terminology was by Muffler and Cataldi (1978), who introduced the hierarchy of terms in Table 5, corresponding to nested partitions of a McKelvey diagram.

The distinction between "accessible" and "inaccessible" was meant to be a depth criterion, set by the practicality and cost of production drilling "at some reasonable time in the future." The distinction between "useful" and "residual" was defined as "a subjective aggregate of predicted technology and economics at some reasonable future time." The distinction between "economic" and "subeconomic" reflects extraction technology, geological characteristics of the site, grade of the resource, and sophistication of the surface plant.

Table 5: Hierarchy of geothermal resource categories. Level of indentation indicates rank. Based on Muffler and Cataldi (1978, Tab. 1 p. 60).

D. Revised Resource Terminology

In order to specify the various concepts, we introduce here the following notation:

$$\int F(T) [\text{constraint 1}][\text{constraint 2}] dV$$

This means integration of the function F of temperature, subject to several constraints, over a space $V(x, y, z)$. The constraints, written in square brackets, are regarded as logical functions, taking one of only two values, 0 and 1, which multiply $F(T)$. Thus, in integrating through a given point (x, y, z) , $F(T)$ is added to the integral if both constraints are equal to 1. If either is zero $F(T)$ is not added. The logical variables were named "relational statements" by Iverson (1973). They are sometimes called "indicator functions" as they operate similarly to the Kronecker delta and Heavyside step functions.

This notation has been termed the Iverson convention (Knuth, 1992) and will be familiar to programmers of the computer language known as APL (Iverson 1962). The square bracket is derived from the International Business Machines, Inc. (IBM) implementation of APL on a track-ball typewriter. The advantage of this notation is that operations on the indices of summation are eliminated, along with complicated expressions in subscripts and superscripts (Knuth, 1992).

We quantify the notion of "accessibility" by supposing that it is possible to define now, at the present time, a cut-off depth, Z_d , below which drilling is not feasible. We further simplify the characterization by absorbing "technological feasibility" into "economic viability" and delete the terms "useful" and "residual" from the hierarchy. We combine all the economic factors into a single measure of performance, the internal rate-of-return on investment, e , and suppose that it is possible to define, now, at the present time, a cutoff, E_r , below which production is not feasible.

The redefined "accessible resource base" Q_a and "economic accessible resource base" Q_{ae} can then be written as in Table 6, where C is the average volumetric heat capacity of the rock in the volume of integration, T_o is the ambient surface temperature, Z_d is the maximum feasible depth for drilling, and E_r is the lowest acceptable rate of return.

Geothermal resource base:
accessible resource base:
$Q_a = \int C(T-T_o) [z \leq Z_d] dV$
economic accessible resource base:
$Q_{ae} = \int C(T-T_o) [z \leq Z_d] [e \geq E_r] dV$
HDR resource base:
$Q_{ha} = \int C(T-T_o) [T \geq T_a] [z \leq Z_d] dV$
$Q_{hb} = \int C(T-T_o) [T \geq T_r] [z \leq Z_d] dV$
$Q_{hc} = \int C(T-T_o) [dT/dz > G_d] [z \leq Z_d] dV$
HDR power resource:
$Q_{hp} = \int C(T-T_r) [T \geq T_a] [z \leq Z_d] dV$

Table 6: Simplified geothermal and HDR resource categories. Temperatures are T_o = ambient surface temperature; T_r = rejection temperature; and T_a = acceptance temperature or minimum rock temperature for electric power production. The depth Z_d is the drilling cutoff, and E_r is the minimum rate of return on investment. Usually $T_o = 15^\circ\text{C}$, $T_r = 90^\circ\text{C}$, $T_a = 150^\circ\text{C}$, $Z_d = 3 \text{ km}, 5 \text{ km}, \text{ or } 10 \text{ km}$, and currently $E_r \geq 12\%$.

E. HDR Resources

HDRAP (1977) defined the HDR resource base as the heat content when rock in excess of 150°C is reduced to 15°C from its initial temperature. Rock initially at temperatures below 150°C was not included. In order to be consistent with the USGS-defined "geothermal resource base," we define the "HDR resource base," Q_{ha} , (Table 6) as the *in situ* heat content of rocks at temperatures above the acceptance temperature T_a ; when cooled from that temperature to the ambient surface temperature T_o ; to a maximum depth of Z_d .

Two variants are Q_{hb} and Q_{hc} , defined in Table 6. The resource base Q_{hb} was introduced by Muffler (1979b). The resource base Q_{hc} was introduced by Heiken et al. (1982) with $G_d = 30 \text{ mK/m}$ as a method of computing the HDR resource base from

geothermal gradient maps.

Cummings et al. (1979) defined the HDR resource base as heat above 150°C at depths less than 10 km. The minimum usable temperature ("rejection temperature") was assumed to be 50°C. We follow this concept and define the "HDR power resource," Q_{hp} (Table 6), as the heat above the rejection temperature, T_r , contained in rocks initially above an "acceptance temperature," T_a , at accessible depths

Armstead and Tester (1987, p. 34-58) used the terms "total crustal heat" and "gross resource base" for the heat content of rocks above 150°C, and "restricted resource base within reach" or "restricted crustal heat resource base" for heat content constrained by maximum depth (Z_d) and minimum useful rock temperature. The "restricted crustal heat resource base" is equivalent to Q_{hb} in Table 6.

F. HDR Reserves

Following the USGS definition of mineral reserves, we could extend this terminology and apply "HDR reserves" to that part of the resource base which is economically extractable by the HDR production techniques developed by Los Alamos National Laboratory at Fenton Hill, New Mexico. Burns and Potter (1990) applied a Net Present Value method to Fenton Hill technology transferred to Clearlake and found a break-even point at 2.4 MWe or 12 MWt in the rock types, stress fields, and geothermal gradients that are found near the city. Here we advocate quantifying "economically" by a single economic index, the internal rate of return on investment. This report does not consider economic factors any further.

V. PREVIOUS ESTIMATES OF HDR RESOURCES AT CLEARLAKE

A. Igneous-related Geothermal Resources

Various models of the thermal behavior of igneous systems have been developed from time to time. Analytical methods were reviewed by Jaeger (1964) and Mongelli (1984).

In order to assess the igneous-related geothermal resources of the United States, Smith and Shaw (1975, 1979) estimated the heat content (Q_a) remaining in young igneous systems to a depth of 10 km. The model required instantaneous emplacement and conductive cooling of a magma body emplaced at a time represented by the age of the youngest silicic extrusive of each system. Cooling of the body by hydrothermal convection was assumed to be offset by the effects of magmatic preheating and additions of magma after the assumed time of emplacement.

They applied their method to the Clear Lake volcanic field. They found that the basic eruptives ranged in age from 2.0E+6 a to <1.0E+4 a, and the silicic eruptives ranged from 10.0E+6 a to 9.0E+4 a. The horizontal surface area of the magma chamber was estimated, from the vent distribution, at 256 km²; and from the -35 mGal Bouguer gravity contour, at 560 km². The volume of the magma chamber was estimated from the gravity contour as between 1370 km³ and 5480 km³, with 1500 km³ regarded as the best estimate. The cooling time was estimated at about 5 Ma (point "CA2" in Smith and Shaw, 1975, Fig. 4 and 1979, Fig. 3). The heat remaining in the system at the present day was estimated to be 3.61E+21 J, as listed in Table 7.

The major uncertainties in this model appear to be in the rate of magmatic resupply and the vigor of hydrothermal circulation. If the magma chamber is periodically resupplied, the rate of cooling is changed substantially. The hydrothermal circulation is not well

of the regional geothermal anomaly (Figure 1, above) probably coincide with the boundaries of the magmatic complex (Urban, et al., 1975).

The temperature distribution in the Franciscan rocks overlying the complex is probably almost entirely controlled by the thermal regime in the highest magmatic sheet. An appropriate distribution is the on-axis cooling distribution of Jaeger (1959). As shown by Jaeger (1959, Fig. 2), the cooling curve changes shape rapidly immediately after magma emplacement, tending towards a straight line with time. For a magma chamber 1 km thick, the temperature profiles become sensibly linear after 50 000 a.

The temperature profiles in the deep wells are linear down to 3.5 km, as shown in Figure 3. The profiles in the impervious cover rocks at The Geysers were shown to be linear down to the first steam entries at a depth of about 1.5 km by Urban et al. (1975). The gradients were also tested by Williams et al. (1993) in three wells in the northwest part of The Geysers steamfield. They found the temperature gradient to variously decrease, remain constant, or increase with depth, in each of the three wells. These rocks and their mesoscopic structures extend to the northeast into the HDR resource.

It is concluded that for the Clearlake HDR resources a linear gradient is a realistic possibility. It is probably the least risky assumption in a statistical sense, as well as convenient for calculations. Accordingly, for this preliminary assessment of heat resources, we use a linear extrapolation of geothermal gradient in depth.

B. Discretized Heat Flow

Discretization of the heat flow at the contour levels shown in the heat flow sketch map of Figure 6, yields the "resource curve" as the collection of straight-line segments in Figure 16. The plot shows the heat flow between any two contours versus accumulated area.

Figure 16: Diagram of heat flow versus cumulative area for The Geysers-Clear Lake area.

C. Boundaries of the HDR Resource Area

We set limits on the HDR resources at the 167 mW/m² (4 hfu) and 335 mW/m² (8 hfu) contours. These cutoffs are selected for reasons as follow.

Steamfield. The higher heat flows occur in convective hydrothermal systems that form the inner boundary of the HDR resources. Thomas (1986) put the outer boundary of

The Geysers steamfield, which is the inner boundary of the HDR resource, at 350 mW/m² (8.4 hfu) for reasons he thought might be as much economic as physical. The heat flow statistics for various regions (Table 3) support Thomas' level.

Hot springs. In Table 2 the heat flow measured in non-hydrothermally affected deep wells ranges from 213 mW/m² to 290 mW/m² (5.1 hfu to 6.9 hfu), averaging 253 mW/m² (6.0 hfu). For the average graywacke of Table 1, this corresponds to temperature gradients in the range 66 mK/m to 90 mK/m, averaging 79 mK/m. Higher heat flows are due to proximity to hydrothermal sources (suffix "h" in Table 2). The flows range from 375 mW/m² to 903 mW/m² (9.0 hfu to 21.6 hfu), corresponding to temperature gradients of 116 to 280 mK/m.

The highest gradient in table 2 is the 323 mK/m of the well "Bradley Mining Company 1," which was drilled to intersect the Sulphur Bank Hot Spring. Burns and Potter (1990, Fig. 4) used drillers' data to estimate a temperature gradient of 410 mK/m for this well, and flow line temperatures yield estimates of 504 mK/m and 531 mK/m. It appears that heat flows above 375 mW/m² (9.0 hfu) are hot spring-affected, while flows below 290 mW/m² (6.9 hfu) are not.

The effect of the hot spring at Sulphur Bank Mine is also shown in Figure 4 by the concave, sharp spike at the right-hand end. The 300°C isotherm lies at a general depth of 3.2 km to 3.1 km (10 600 to 10 200 ft) below the ground surface in the area between the Wilson and the Borax Lake wells and then rises sharply to a depth of about 0.9 km (300 ft). The boundary of the hydrothermal effect is marked by a change in heat flow from about 261 mW/m² to 385 mW/m² (6.2 to 9.2 hfu).

Inner boundary. The temperature profile of Figure 4 and the discretized areas of Figure 16 are different representations of the same phenomenon. By comparison of the two figures, one sees that it is likely that the boundary of hydrothermal areas is the 335 mW/m² (8 hfu) contour. Values higher than 335 mW/m² (8 hfu) may be due to heat flow conducted laterally from hydrothermal circulation systems, or they may indicate regions of higher rock permeability that allow convective heat transfer. Accordingly, we adopt 335 mW/m² (8 hfu) as the inner boundary of the HDR resource area.

Outer boundary. For the outer boundary, we adopt the heat flow 167 mW/m² (4 hfu), in part because of the comments of Urban et al. (1975). The boundary has been well-defined by the work of Walters and Combs (1989, 1992). The geothermal gradient at that contour is about 60 mK/m, about twice the cutoff adopted by Heiken et al. (1982), so the choice is conservative.

D. Calculation of Resources

The resource categories Q_a , Q_{ha} , and Q_{hp} were defined in Table 6. The calculations for the Clearlake region are set out in Table 8. The results are, for the geothermal resource base, Q_a , 1.68E+21 J; for the HDR resource base, Q_{ha} , 1.39E+21 J; and for the HDR power resource, Q_{hp} , 1.00E+21 J. The HDR power resource Q_{hp} is equivalent to 2.78E+11 MWh, or 1.72E+11 bbls of oil (Armstead and Tester, 1987, Unit Conversion Table).

<i>H1-H2</i>	4-5	5-6	6-7	7-8	8-12	4-8	hfu
<i>xy</i>	214	178	174	58	9	634	km ²
<i>G</i>	63	77	92	106	141	---	mK/m
<i>za</i>	2366	1936	1638	1420	1065	---	m
<i>T5</i>	333	403	473	544	720	---	°C
<i>Qa</i>	462	469	542	208	45	1681	E+18 J
<i>Qha</i>	346	387	471	187	42	1392	E+18 J
<i>Qhp</i>	232	277	353	145	35	1007	E+18 J

Table 8: Geothermal resources of the Clearlake region. This table represents the accessible geothermal resource base *Qa*; HDR resource base *Qha*; and HDR power resource *Qhp*, as defined in Table 7, for the heat flow map of Figure 6. The heat flows at the lower and upper sides of each contour strip are *H1* and *H2*, respectively. The area of the strip is *xy*. The average geothermal gradient at the midline is *G*. The acceptance temperature is *Ta*, and the rejection temperature is *Tr*. The depth of the acceptance isotherm is *Za*. The projected temperature under the midline at a depth of 5 km is *T5*.

The resources were found from

$$Qa = C * [(To + T5)/2 - To] * xy * 5000;$$

$$Qha = C * [(TO - T5)/2 - TO] * xy * (5000 - Za); \text{ and}$$

$$QHP = C * [(Ta - T5)/2 - Tr] * xy * (5000 - Za),$$

where $TO = 15.6^{\circ}\text{C}$, $Tr = 90^{\circ}\text{C}$, $Ta = 150^{\circ}\text{C}$, C is the volumetric specific heat taken as $2.72\text{E}+6 \text{ J/m}^3 \cdot \text{K}$, and L is the average bulk thermal conductivity at 2.97 W/m.K .

E. Electric Power Potential

The HDR power resource, *Qhp*, of $1.0\text{E}+21 \text{ J}$, has to be reduced by factors for recovery and conversion efficiency to determine the potential electric power production. Relevant factors include the available energy fraction, which measures an energy recovery component *Fa* expressed as the ratio of recoverable energy to resource base, taking account of thermal conversion efficiency associated with the second law of thermodynamics (Armstead and Tester, 1987). A second factor is the wellhead fraction *Fw*, which accounts for friction, work, and heat flow losses associated with energy extraction. A third factor is the power plant fraction *Fp*, which accounts for losses between the wellhead and the power plant. The fourth factor is the busbar fraction *Fb*, which is associated with the losses associated with the conversion of heat to electricity.

The electric energy potentially deliverable to the busbar *Qhe*, is then computed by $Qhe = Fa * Fw * Fp * Fb * Qhp$.

The factors for geothermal resources of various types were estimated by EPRI, as shown in Table 9. EPRI's estimate of overall conversion efficiency for HDR applies to a higher production temperature range than does our estimate of *Qhp*. However, using EPRI's fraction, *Qhe* is found to be approximately $1.61\text{E}+9 \text{ MWhe}$, or $1.89\text{E}+5 \text{ MWye}$, or over 135 years at the current production rate of 1380 MWe (Mock 1992) at The Geysers. The overall conversion factor, or ratio of recovered electric power to thermal energy *in situ*, is 0.0058 in EPRI (1978), the most recent North American estimate known.

Recently, Kruger et al. (1996) and Kuriyagawa et al. (1996) have published information from Japan that suggests that the conversion factor might be considerably higher, perhaps as high as 0.03. This higher figure would materially alter the estimate given above. The estimate of Q_{he} given above is therefore a tentative result, which should be adjusted appropriately when conversion figures are available for the Clearlake region.

Reservoir type	$T1$	$T2$	Fb	Fp	Fw	Fa	F
Vapor-dominated	227	177	0.72	0.95	0.3	0.09	0.018
Liquid-dominated	227	177	0.72	0.6	0.4	0.09	0.016
Hot Dry Rock	302	177	0.65	0.6	0.08	0.185	0.0058
Geopressured	227	177	0.75	0.6	0.5	0.009	0.020

Table 9: Efficiencies of power production from various categories of geothermal resources. Fractions are Fa , available energy; Fw , wellhead; Fp , power plant; and Fb , busbar. $T1$ and $T2$ are assumed conditions: $T1$ is the initial reservoir temperature, and $T2$ is the temperature at which production ceases to be economical. From EPRI (1978).

VII. SUMMARY

The HDR geothermal resources of northern California are that part of The Geysers-Clear Lake geothermal anomaly that surrounds The Geysers steamfield. The HDR resource area is selected as that part of the geothermal resource area with heat flows between 167 mW/m² (4 hfu) and 335 mW/m² (8 hfu). This region has a surface area estimated here at approximately 624 km².

The Geysers-Clear Lake geothermal anomaly is currently regarded as a consequence of San Andreas tectonics. As the northern tip of the San Andreas traveled northward, "unzipping" the Pacific from the North American plate, a wave of uprisen asthenosphere ("slabless window") followed on the inshore side, like an asymmetrical version of the stern wave on a ship. This led to mafic magmatism and crustal underplating. About 1.5 Ma after passage, the heat from the basaltic magmas triggered crustal melting and silicic volcanism, which persisted for another 1.5 Ma.

Geological and geophysical understanding of the Clear Lake volcanic field is continually evolving and this affects estimates of the heat resource. In national resource assessments made two decades ago, the area was grouped with other "igneous-related" geothermal resources, and the heat content was estimated using a complex magmatic emplacement and cooling model. The current view is that the magma chambers are sheeted intrusions, forming tabular, sill-like, multicompositional bodies across the area of the geothermal anomaly. The effect at shallow depth is to generate almost one-dimensional heat flow, with flux lines vertical and parallel across large areas. The geothermal gradients are linear down to 3.6 km, and at present, we see no problem in projecting these to 5 km for resource estimation purposes. It is suggested that the temperature distribution with depth might approximate the "on-axis" distribution of Jaeger (1959) down to the top of the highest cooling sill. Below that there are expected to be substantial fluctuations above and below partially solidified cooling sheets with the possibility (Jaeger, 1959) of ultra-high temperatures between sheets.

The heat resources for the HDR portion of The Geysers-Clear Lake geothermal field are estimated in Table 8. The estimated accessible geothermal resource base (Qa) is 1.68E+18 J; the HDR resource base (Qha) is 1.39E+18 J; and the HDR power resource (Qhp) is 1.01E+18 J. The HDR power resource (Qhp) is equivalent to 2.78E+11 MWht, or 1.72E+11 bbls of oil.

The HDR potential power resource (Q_{hp}) has to be reduced by factors for recovery and conversion efficiency to determine the HDR electric power production potential (Q_{he}).

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