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Energy Research and Development Administration

Division of Geothermal Energy

Hot Dry Rock Geothermal Energy: Status of Exploration and Assessment

Report No. 1 of the Hot Dry Rock Assessment Panel

June 1977

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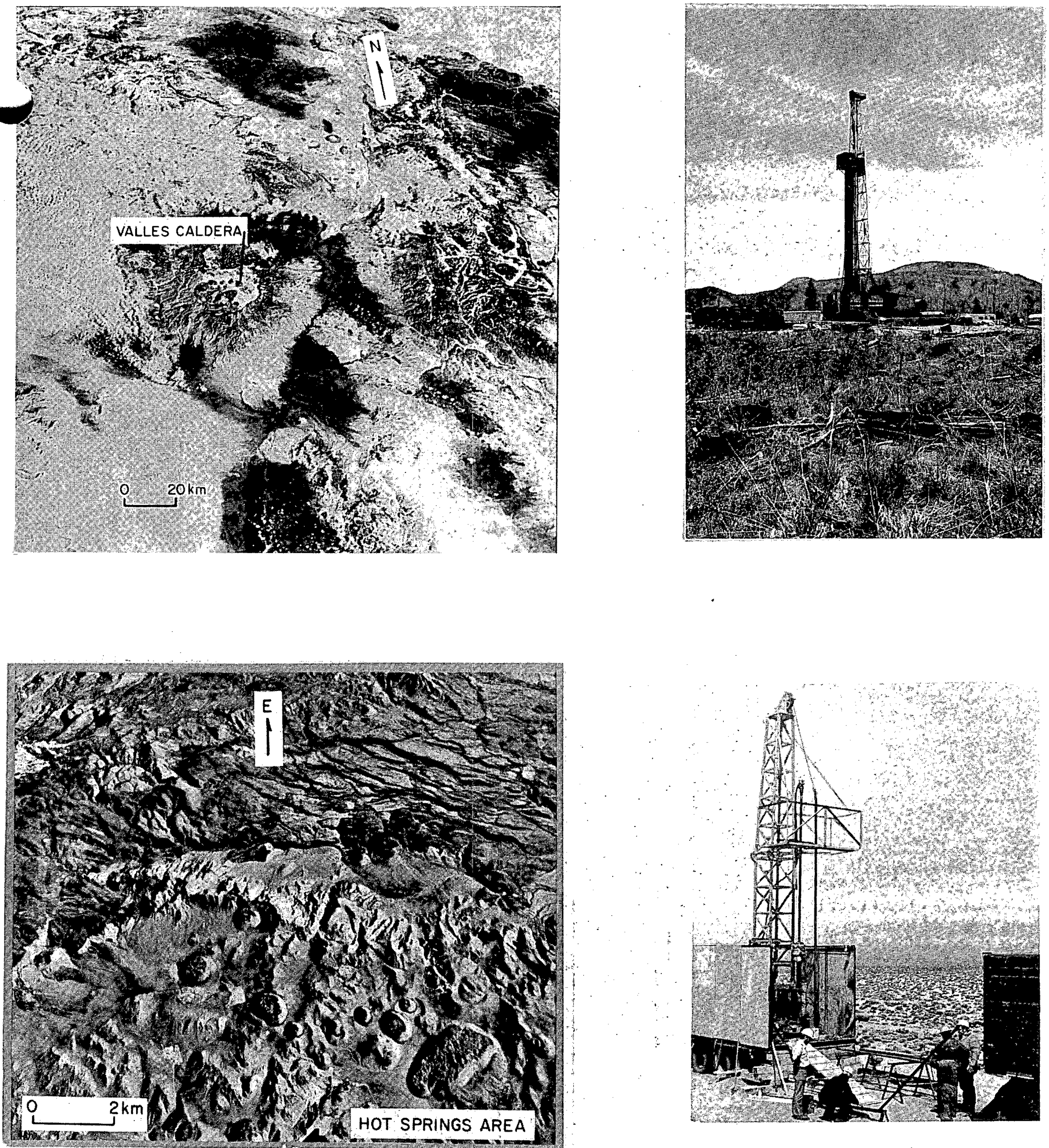
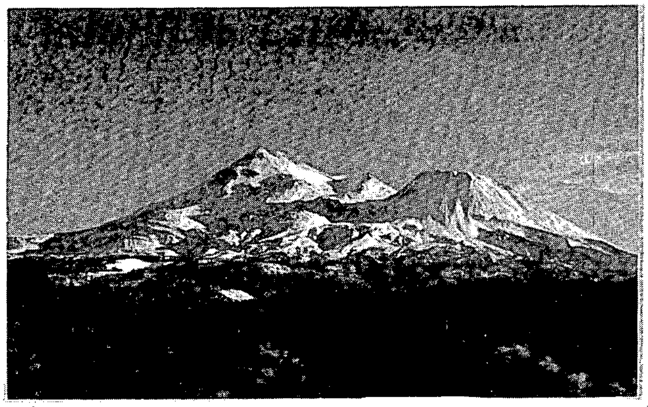


Figure 1.1 Currently funded ERDA hot dry rock geothermal project areas.
(a) Fenton Hill Site, Valles Caldera, New Mexico
(b) Coso Hot Springs Area, China Lake, California



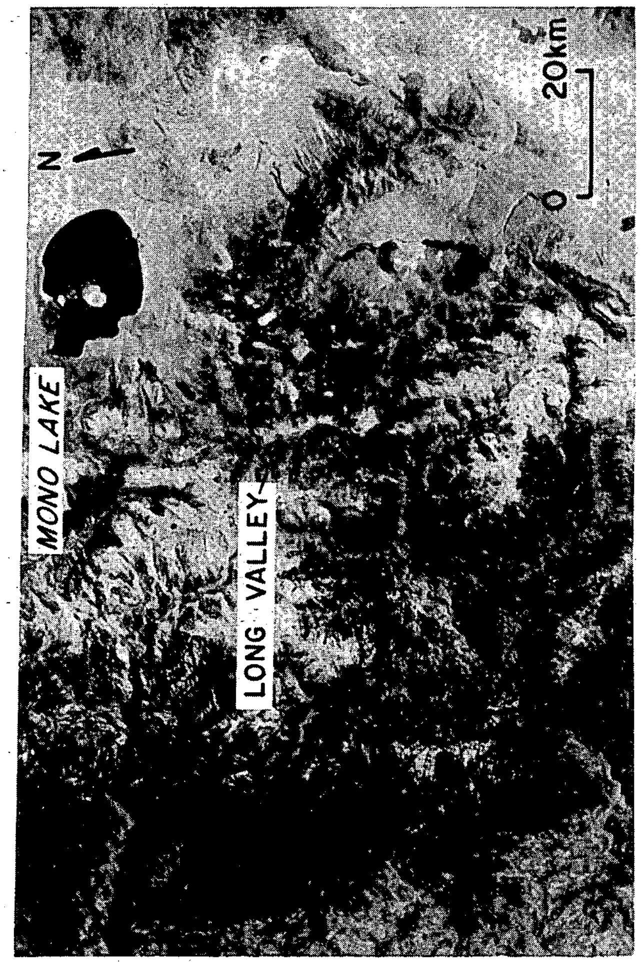


Figure 1.2 Areas recommended by HDRAP for potential future assessment of HDR geothermal resources.

(a) Mt. Shasta, California

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1. SUMMARY AND RECOMMENDATIONS

1.1 Summary

This report summarizes the status of knowledge of attempts to utilize hot dry rock (HDR) geothermal energy. It contains (1) descriptions or case histories of the ERDA-funded projects at Marysville, MT, Fenton Hill, NM, and Coso Hot Springs, CA; (2) a review of the status of existing techniques available for exploration and delineation of HDR; (3) descriptions of other potential HDR sites; (4) definitions of the probable types of HDR resource localities; and (5) an estimate of the magnitude of the HDR resource base in the conterminous United States. The report purposefully is limited in scope to that part of HDR resource assessment related to the determination of the extent and character of HDR, and does not address technological, economic, societal, governmental, or environmental aspects of HDR utilization.

Two general categories of HDR can be defined; they are related to different types of heat sources, namely: (1) igneous-related HDR, which exists because of heat transferred to the surrounding crust from bodies of magma, and (2) HDR in the crust, resulting from heat transferred there principally by conduction from the earth's deeper interior. The heat source can be an unusually warm upper mantle, or locally, internal heat sources, principally radiogenic heat or metamorphic (exothermic chemical reaction) heat.

The report focuses on the first category of potential HDR resource, namely the igneous-related type, because our efforts to date have been concentrated there and because it is composed of the high-grade deposits of HDR. The known igneous-related sites within the conterminous U.S. are listed and classified.

We estimate that approximately 74 Q (1 Q = 1,000 Quads) of heat is stored in igneous-related HDR sites within the conterminous U.S. at depths less than 10 km and temperatures above 150°C, the minimum for power generation. (Q = 10^{18} BTU = 10^{21} J; the total U.S. consumption for 1972 was approximately 0.07 Q.) Approximately 6300 Q are stored in the conduction-dominated parts of the crust in the western U.S. (23% of the total surface area), again at depths less than 10 km and temperatures above 150°C. Nearly 10,000 Q are believed to be contained in crustal rocks underlying the entire conterminous U.S., at temperatures above 150°C. Clearly the resource base is significantly larger for lower grade heat. Table 1.I summarizes the estimated magnitude of the HDR resource base in various types of continental crust.

It is important to emphasize that we make no attempt in this report to assess the extraction or conversion efficiencies required to interpret this large resource base in terms of economically usable heat, that is "resources." This requires knowledge of extraction technologies and economic issues, purposefully excluded from this report. These essential items should be the focus of future topical reports.

It is also noteworthy that in most geothermal systems HDR and hydrothermal geothermal energy coexist -- their distribution in both position and time may change as the system evolves. For practical reasons in the future it may be

Table 1.I HDR Resource Base of the United States, in units of 10^{22} calories.

	HDR Resource Base d < 10 km T > 15°C		Fraction of the HDR Resource Base (4)			% of Surface
	USGS Circular 726	This Report	d<10 km T>150°C	d<6 km T>150°C	d<3 km T>150°C	
Igneous Related	105(2)	77(3)	74	24	3.5	0.093
Basin-Range Type	8,230	8,305	6,302	987	0	23.8
Eastern Type	15,446	14,803	3,573	0	0	75.3
Sierra Nevada Type	130	120	0	0	0	0.87
Total	23,911	23,305	9,949	1,011	3.5	

(1) Units of Q are: Q = 10^{18} BTU = 10^{21} J = 0.24 x 10^{21} cal. Approximate US consumption for 1972 was 0.07Q.

(2) Total based on summing individual igneous systems, including Hawaii and Alaska. Contains both molten (55Q) and crystallized (50Q) parts.

(3) Total based on simple integration using the average-igneous geotherm from Figure 5.7.2, hence should be treated as close-order-of-magnitude (±50%) estimate. Does not include latent heat of magma.

(4) Heat contents were calculated assuming all the rock at depths shallower than the indicated depths (10, 6, and 3 km respectively) and in excess of 150°C is reduced to 15°C from its initial temperature. Rock initially at temperatures below 150°C is not included. The heat capacity assumed was 2.71 x 10^{-6} Q/km³°C, equivalent to approximately 0.65 cal°C/cc. Note, that dry granite at low temperature has a specific heat of about 0.52 cal°C/cc and basalt about 0.60; the crust is intermediate in composition and warm at moderate depth, hence the value of 0.65 is probably correct to about ± 10%.

important to focus interest on that part of the HDR resource base associated with hydrothermal systems. This, in fact, is the case with the current exploration and assessment activities at Coso, Valles Caldera (Fenton Hill), and Long Valley, but the HDR potential of the Geysers, Imperial Valley, and Roosevelt Hot Springs warrants careful study.

To date, exploration for HDR has been focused on regions containing large, young silicic volcanic centers (Valles Caldera, NM; Coso Area, CA) or sites which, prior to drilling, were believed to be of this general type (Marysville, MT). Indeed, these igneous-related sites are likely to constitute the highest grade deposits of relatively dry geothermal energy. However, a fundamental point of this report is that these localities constitute only a small fraction of the HDR resource base -- by far the largest part is stored in the warm crystalline rocks of the crust. Of approximately 3000 Q at temperatures above 150°C at depths less than 10 km, 98% lies at depths exceeding 6 km in the conduction-dominated parts of the crust.

Exploration for HDR and HDR evaluation, so far, has proceeded by a two-step process in which the existence of a geothermal system is inferred largely from its surface manifestations (hot springs, fumaroles) and/or associated young volcanism, implying a heat source at depth. The second step consists of defining the possible HDR contained in the system by a process of elimination -- namely, the hydrothermal part of the system including the cool part of the hydrothermal system in which recharge occurs is identified, principally by use of geophysical techniques and drilling. The remainder of the geothermal system could be HDR.

Several stages in the exploration for HDR (see Table 3.4.I) can be defined -- which we expect will remain unchanged even as our knowledge of techniques evolves, namely: (1) development of a rationale for selection of a region to be investigated; (2) region selection with compilation and review of available data; (3) acquisition of new data using surface geological and geophysical techniques and targeting of drill sites; (4) development of pre-drilling geological models; (5) planning and carrying out a heat flow survey, defining and conducting slim hole drilling, and confirmation of pre-drilling models; (6) refinement, rejection, and iteration of the geological model(s); and (7) deep drilling, data analysis, and evaluation.

The exploration at Marysville, MT, did not include the last part of stage 5, slim hole drilling. Discovery of the deep hydrothermal system there (although repeatedly and explicitly stated as one possible pre-drilling geological model) was not confirmed until an expensive (production-sized) hole was drilled. This experience emphasizes the need for slim hole drilling techniques for HDR resource assessment.

Each of the HDR projects so far fielded had a different rationale -- or none explicitly defined for HDR resource assessment. The goal of the Los Alamos Scientific Laboratory (LASL) project at Fenton Hill, NM, was to demonstrate the twin hole and hydraulic fracture technique of HDR energy extraction. The goal of the Battelle Northwest Laboratory's drilling program at Marysville, MT, initiated under NSF-RANN, was to extract geothermal energy from shallow hot rock -- not to assess the resource. The stated goals at Coso, CA, are to develop slim hole drilling techniques for resource assessment and to determine the HDR potential of this locality.

Experience in exploration for both HDR and hydrothermal geothermal systems has shown that these systems have no simple, reliable, nor unambiguous geophysical signatures. Necessary but not sufficient conditions can be defined. Drilling, thus far, has proved to be the only reliable means of precisely determining rock properties and temperature at depth. For this reason, it is important that relatively inexpensive drilling techniques be developed for use as an exploration and resource assessment tool.

1.2 Recommendations

The recommendations outlined in Section 6 are summarized below:

- Stress the development and use of quantitative geological models in HDR resource assessment. These models, developed on a site-by-site basis, should evolve by a process of iteration and refinement as additional data are acquired.

- Develop a means for HDR resource assessment. This will require a long-term commitment, probably 7 to 10 years. Data acquired and geological models produced, however, will be directly applicable to solution of problems in extraction of energy.

- Include in program planning the time required for research and exploration for development of the first firmly based quantitative geological model leading to assessment of the HDR resource base, generally 2 to 3 yr.
- Recognize that HDR resource assessment requires that areal and regional data be acquired before the heat source responsible for a given geothermal system can be characterized and the resource base assessed.
- Apply all appropriate exploration techniques; encourage overlap and redundancy until the relative efficiency of various techniques is well established.
- Establish a center for accumulation of data and materials such as cores, with adequate curatorial and library support facilities, with staff to accomplish systematic publication of results and project status reports, and to accomplish appropriate information coordination and dissemination functions.
- Further develop borehole measurements and slim hole drilling technology. Drilling is, and probably will remain, an essential part of HDR resource assessment.
- Continue to emphasize heat flow surveys as a primary tool for HDR resource assessment, supported by geology and other geophysical methods. However, for igneous-related systems, it is now apparent that powerful inferences can be drawn from data on the composition, volume, and age of associated volcanic rocks -- research, here, should be encouraged and the techniques for quantitative geological modeling, developed.
- Proceed in parallel with research of conduction-dominated HDR areas and with that on igneous-related geothermal systems, particularly in the western U.S. where the crust at attainable depths (6 to 10 km) is warm or hot.
- Encourage deep drilling to gain an understanding of the deep parts of igneous-related geothermal systems. This will require, ultimately, penetration into a magma chamber (4 to 6 km depth and about 800°C).

- Publish a future HDRAP report detailing the HDR associated with known or producing hydrothermal systems, namely the Geysers, three sites in the Imperial Valley (Salton Sea, East Mesa, and Heber), and Roosevelt Hot Springs. Secondary methods of reservoir stimulation could play an important role in developing HDR. It is already recognized that HDR and hydrothermal geothermal systems coexist at Coso, Fenton Hill, and Long Valley.
- Support additional geophysical and geological investigations at the Valles Caldera and Marysville designed to better define the heat source. This program will take advantage of already existing deep drill holes and will contribute to calibration of exploration methods as well as provide quantitative resource assessment models. (It should be noted that the panel disagrees on the importance of additional work at Marysville; the majority view, however, favors further investigation of the system to understand and thereby to avoid this economically undesirable type of site).
- Initiate resource assessment projects at the initial four sites recommended by HDRAP: Long Valley, CA; Mt. Shasta, CA; San Francisco Peaks, AZ; and Medicine Lake Highland, CA. These represent several different types of igneous-related HDR resource sites, and they will serve as valuable case histories for development and calibration of exploration techniques for resource assessment.
- Vigorously pursue current activities at Coso, including development of slim hole drilling methods for resource assessment. Explorations should be areal in extent, not restricted to the central dome field, and focused on quantitative characterization and understanding of the heat source.

1.3 Authorship and Acknowledgments

Several individuals carried the editorial load in the preparation of this report, notably Jim Combs, Robert Mallis, Thomas McGetchin, John Rowley. McGetchin served as editor-in-chief and had overall responsibility for organization and preparation of this document. Carolyn Nelson supervised preparation of the manuscript with the help of Barbara Hahn and Sue Noel. Luween Smith drafted the original figures. Jeannette Mortensen edited the

final stages of the manuscript. Various parts of the manuscript were contributed by more than a dozen authors: Part 1 was prepared by McGetchin and Rowley, with the assistance of the Hot Dry Rock Assessment Panel (HDRAP); Part 2, R. L. Christiansen, T. McGetchin, M. Scheve, R. Mallis, and J. Rowley; Part 3, A. W. Laughlin and F. West (3.1), W. McSpadden and J. Upton (3.2), J. Combs and W. Duffield (3.3), and J. Rowley (3.4); Part 4, J. Combs with assistance from T. McGetchin, J. Rowley, R. Mallis, F. West, and T. Shankland; Part 5, R. L. Smith and T. McGetchin, with site summaries by R. Bailey (5.5.A), E. Wolfe, G. Ulrich, and R. Moore (5.5.B), J. Eichelberger (5.5.C), and R. Christiansen (5.5.D). The site abstracts contained in the appendix were prepared by G. Heiken, with the assistance of several people, and are based on both published and unpublished reports using site lists generated by R. L. Smith and by Heiken, Laughlin, and McGetchin. The report was reviewed by the members of HDRAP and does reflect the consensus of that Panel, although not necessarily of all its members on all matters.

We wish to acknowledge sources of illustrations that we were permitted to reprint: Figures 1.1 and 3.3.1, from W. A. Duffield, "The Late Cenozoic Ring Faulting and Volcanism in the Coso Range Area of California," Geology, v. 3, 1975, pp. 335-338. Figures 3.2.2-5, from D. D. Blackwell and C. G. Baag, "Heat Flow in a Blind Geothermal Area Near Marysville, Montana," Geophysics, v. 38, 1973, pp. 941-956. Figures 5.5.1 and 2, from R. A. Bailey et al., "Volcanism, Structure, and Geochronology of Long Valley Caldera, Mono County, California," Journal of Geophysical Research, v. 81, no. 5, 1976, pp. 726 and 728, copyrighted by the American Geophysical Union. Figure 5.5.3, from M. F. Kane et al., "A Gravity and Magnetic Investigation of the Long Valley Caldera, Mono County, California," Journal of Geophysical Research, v. 81, no. 5, 1976, p. 755, copyrighted by the American Geophysical Union. Figure 5.5.4, from D. P. Hill, "Structure of Long Valley Caldera, California, From a Seismic Refraction Experiment," Journal of Geophysical Research, v. 81, no. 5, 1976, pp. 746 and 750, copyrighted by the American Geophysical Union. Figure 5.5.5, from M. F. Kane et al., "A Gravity and Magnetic Investigation of the Long Valley Caldera, Mono County, California," Journal of Geophysical Research, v. 81, no. 5, 1976, p. 761, copyrighted by the American Geophysical Union. Figures 5.5.6 and 7, from A. H. Lachenbruch et al., "Geothermal Setting and Simple Heat Conduction Models for the Long Valley, Caldera," Journal of Geophysical Research, v. 81, no. 5, 1976, pp. 771 and 773, copyrighted by the American Geophysical Union. Figure 5.5.8, from W. D. Stanley et al., "Deep Electrical Investigation in the Long Valley Geothermal Area, California," Journal of Geophysical Research, v. 81, no. 5, 1976, p. 813, copyrighted by the American Geophysical Union. Figure 5.5.15, from T. R. LaFehr, "Isostasy and Crustal Structure in the Cascades," Journal of Geophysical Research, v. 70, no. 22, 1965, p. 5585, copyrighted by the American Geophysical Union. Figure 5.5.18, C. A. Anderson, "Volcanoes of the Medicine Lake Highland," University of California Publications in Geological Sciences, v. 25, no. 7, pp. 347-422, published in 1941 by the Regents of the University of California; reprinted by permission of the University of California Press. Figure A.9.1, from C. A. Anderson, "Volcanic History of Clear Lake Area," GSA Bulletin, v. 47, 1936, pp. 634-635. Figures A.10.1 and A.11.1, from "Magma Beneath Yellowstone National Park," Science, v. 188, 1975, pp. 787-796, copyright 1975 by the American Association for the Advancement of Science.

2. INTRODUCTION

2.1 Purpose

The objectives of this report are to:

(1) Define what is meant by hot dry rock (HDR), the HDR geothermal resource base, and some related terminology.

(2) Describe and summarize the present status of HDR exploration and evaluation, including summaries of sites explored to date.

(3) Review the techniques and criteria that may be used in exploring for specific HDR systems.

(4) Describe the exploration status and the characteristics of known sites that have been explored for HDR in terms of their physical properties.

(5) Recommend directions for future research to improve the knowledge of the magnitude of the U.S. HDR geothermal resource base.

(6) Recommend a rational approach for selection of future U.S. HDR regional sites.

(7) Recommend a list of potential HDR regional geothermal sites based on available data.

2.2 Hot Dry Rock Assessment Panel (HDRAP)

The HDRAP is an informal working group established to assist ERDA and its contractors in coordinating the HDR Program activities and in maintaining a free flow of information about actions and problems dealing with resource base assessment and characterization. The panel provides a forum for the interaction between the ERDA Division of Geothermal Energy, ERDA National Laboratories, the U.S. Geological Survey, other Federal agencies, contractors, the interested academic community, and potential industrial users.

The principal duties of the panel are:

(1) To provide, organize, and analyze technical information and interpretations related to the location and character of HDR within the United States;

(2) To contribute to the development of a rationale, policies, and approaches for characterizing HDR;

(3) To assist in identifying specific locations for HDR assessment and exploration projects;

(4) To review technical plans, proposals, and reports related to HDR assessment and exploration projects.

The panel has been instructed to consider principally the questions of HDR resource base assessments and not to be concerned with political, institutional, legal, environmental, or economic issues. Also, matters relating to extraction technologies and research and development projects on extraction feasibility demonstrations are not to be considered.

The panel reports directly to the Manager of the Hot Dry Rock Program, ERDA's Division of Geothermal Energy. Reporting includes minutes of each HDRAP meeting and, as appropriate, special reports documenting the HDRAP studies. Panel meetings are held two to four times per year as required and normally last a full day. The Advanced Systems Branch Chief or his ERDA representative is Chairman of the panel, and a representative from Los Alamos Scientific Laboratory (LASL) serves as the Secretary. LASL is responsible for coordinating reports and activities of the panel. Table 2.I lists current members.

2.3 Definitions and Terminology

Resource base: Heat in the earth. In this report we consider geothermal heat stored in the earth at depths not exceeding 10 km to be the resource base.

Resource: That part of the (any) resource base (including reserves) likely to become economically available. A general definition applying to minerals, petroleum, or heat.

Geothermal resources: Heat stored in the earth's crust, both identified and undiscovered, that is, recoverable using current or near-current technology, regardless of cost.

HDR geothermal resource: Heat stored in rocks within 10 km of of the surface from which the energy cannot be economically produced by natural hot water or steam.

Geothermal system: A portion of the earth's crust containing an anomalous concentration of heat. Geothermal systems include one or more of

Table 2.I Hot Dry Rock Assessment Panel Membership.

August 1976

Carl Austin
Department of the Navy
Naval Weapons Center
China Lake, CA 93555

Jim Combs
The University of Texas at Dallas
Center for Energy Studies
P. O. Box 688
Richardson, TX 75080

Robert L. Christiansen
U. S. Geological Survey
Coordinator, Geothermal Energy Research Program
345 Middlefield Rd.
Menlo Park, CA 94025

Myron H. Dorfman
University of Texas at Austin
Department of Petroleum Engineering
Austin, TX 78712

A. William Laughlin
Geoscience Group, MS 978
Los Alamos Scientific Laboratory
University of California
P. O. Box 1663
Los Alamos, NM 87545

David B. Lombard
Advanced Systems Branch Chief
Geothermal Energy Division
U. S. Energy Research and Development Admin.
20 Massachusetts Avenue, NW
Washington, DC 20545

Thomas McGetchin
Geoscience Group, MS 978
Los Alamos Scientific Laboratory
University of California
P. O. Box 1663
Los Alamos, NM 87545

L. J. P. Muffler
U. S. Geological Survey
345 Middlefield Rd.
Menlo Park, CA 94025

Clayton R. Nichols
Resource & Reservoir Assessment Branch
Geothermal Energy Division
U. S. Energy Research & Development Admin.
20 Massachusetts Avenue, NW
Washington, DC 20545

Denis Norton
University of Arizona
Department of Geosciences
Tucson, AZ 85721

John C. Rowley
Geosciences Division, MS 570
Los Alamos Scientific Laboratory
University of California
P. O. Box 1663
Los Alamos, NM 87545

Martin R. Scheve
Program Manager
Geothermal Energy Division
U. S. Energy Research & Development Admin.
20 Massachusetts Avenue, NW
Washington, DC 20545

James J. Sheff
Battelle-Pacific Northwest Laboratories
Battelle Boulevard
Richland, WA 99352

Robert L. Smith
U. S. Geological Survey,
Branch of Field Geochemistry & Petrology
National Center Bldg., Stop 95
Reston, VA 22092

W. D. Stanley
U. S. Geological Survey
Denver Federal Center
Denver, CO 80225

Joseph Upton
Battelle-Pacific Northwest Laboratories
Battelle Boulevard
Richland, WA 99352

the following types of geothermal heat: magma, hydrothermal convection regions, or simply warm or hot rocks in conduction-dominated regions of the system.

Resource characterization: The study of the nature, origin, history, evolution, and occurrence of the various types of geothermal resources within a geothermal system. Economics of recoverability requires reservoir characterization, which addresses the properties of the rocks of the producing zones of a geothermal system, or specified parts of one, in terms of the behavior of the reservoir under geothermal energy recovery operations.

Resource assessment: A quantitative estimate of the geothermal resources stored within a specified geothermal system or systems. The act of creation of a resource model, as defined below.

Resource models: A quantitative estimate and description of the quality, quantity, and location of stored heat, including magma, hydrothermal, or HDR. Because, the term resource implies recoverability, such models ultimately must address the economic and technological problems and the efficiencies in each step of the recovery process.

HDR target area: A general geographic location that because of surface and subsurface geologic, geophysical, and geochemical indicators appears to be a favorable place for HDR resource prospect.

Geological models: A three-dimensional description of the physical and chemical properties of a geothermal system. It would normally include: (a) distribution of major rock types, physical properties, and spatial distribution -- generally contained in detailed structural cross section(s); (b) historical evolution of the region; (c) chemical and petrological evolution of the system; (d) the nature and configuration of the heat source(s); (e) the hydrology of the system; (f) quantitative description of the thermal evolution of the thermal anomaly, its present thermal state, and heat transfer processes; and (g) both qualitative and quantitative modeling of the major geological processes active within the system, including hydrology.

Heat sources: Geothermal systems result from heat sources within the earth's crust. These are known to include: (a) recent (Quaternary) or large Tertiary igneous intrusions and (b) extended regions of high heat flow due, for example, to a thin crust, or areas with unusually high radioactivities.

Hot dry rock site: A somewhat subtle but real and bothersome ambiguity commonly arises over use of the term "site." The term carries a quite different meaning to different people depending on their experience especially in terms of scale. We offer the following in an attempt to clarify this usage.

Most commonly the term "site" refers to a location designated for a specific purpose. An HDR "site" is an area on the surface under which an HDR resource prospect may be found. The terms region, area, locality, and drill site carry specific areal meanings in terms of their relationship to a given geothermal system. These various areal extents, as commonly used, are listed below; this terminology has been used throughout the remainder of this document.

Site Terminology	Approximate Linear Dimension (km)	Approximate Areal Dimension (km^2)
Regional site	100	10^4
Areal site	10 to 100	100 to 10^4
Local site	1 to 10	1 to 100
Drill site	< 1	< 1

Geothermal gradient: The increase of temperature with depth in the earth's crust, which varies from place to place due to differences in thermal conductivity of rock, heat flux, and locally, water circulation. For engineering purposes, the normal geothermal gradient is usually taken to be approximately 25 to 30°C/km.

Heat flow: The flux of heat (or thermal energy) per unit area per unit time normal to the surface. The worldwide average value is usually considered 1.5 HFU (heat flow units) in $\mu cal/cm^2 sec$ (or 6.3×10^{-2} W/m^2). The heat flow is usually obtained by measuring the geothermal gradient in a shallow borehole and thermal conductivities of the rocks penetrated, then deriving the heat flux as the product of these values.

Thermal anomaly; A perturbation from the normal geothermal gradient as defined on a regional basis. The areal extent and amplitude of the perturbation depend on the nature of the heat source but, in general, thermal anomalies can be either local or subregional in extent. For purposes of discussion, two principal types of thermal anomalies can be recognized and associated with specific types of heat sources (see "heat sources" above). Perturbations associated with igneous heat sources tend to have large amplitudes (commonly in excess of 100% of background) but are local in extent; the thermal perturbation decays and becomes more diffuse as the igneous system ages. Local perturbations within conduction-dominated regions do occur, but they are generally a smaller percentage of background regional temperatures for a given depth. Significant variations in temperature are known to exist along large-scale structural (tectonic) features such as faults or regional fracture systems, but the heat source is commonly not well defined. Contained within each of these thermal anomalies, a corresponding HDR resource may exist (see "Categories of HDR").

Categories of HDR: Two general categories of HDR can be defined, both related to different types of heat sources and both associated with thermal anomalies. The first is igneous-related HDR, which forms from heat transferred to the crust from bodies of magma; HDR may exist in rocks surrounding the magma body or in crystallized magma itself. The second category of HDR is heat stored in rocks of the crust, transferred there principally by conduction from the earth's deeper interior. The source of the heat can be an unusually warm upper mantle, or in some areas, local internal heat sources may exist (principally radiogenic heat although chemical reaction heat may contribute locally).

Exploration: The application of existing geological, geophysical , and geochemical techniques to the search for geothermal systems.

Interpretation: A subjective explanation or description of observed phenomena, such as structure at depth, based on surface mapping or geophysical data. May vary from individual to individual according to personal bias or experience.

2.4 Nature of the HDR Resource Base

Geothermal energy can be characterized and classified in various ways, but like any natural resource it must at some point be considered in terms of its potential availability and use. The HDR resource base is a concept based upon such considerations. The distinction between the terms "resource" and "resource base" is significant, and warrants some amplification.

All the heat in a given volume of rock clearly is not the resource, any more than all the aluminum in the feldspars of the Sierra Nevada is an aluminum resource. According to Schurr and Netschert (1960, Energy in the American Economy, 1850-1975: Baltimore, the Johns Hopkins Press, p. 297) "The resources [of a mineral raw material] consist of that part of the resource base (including reserves) which seems likely to become available given certain technologic and economic conditions." This definition is accepted in the mineral and petroleum industries, and should be used in geothermal resource assessment if the geothermal estimates are to be rationally compared with other sources of energy. Existence of heat in the ground does not qualify that heat as a resource, any more than existence of oxygen in rocks qualifies that oxygen as a resource. Heat in the ground is termed a "resource" only if its economic use can reasonably be foreseen. Given reasonable extraction and conversion efficiencies, only a small fraction in any given volume of ground can be considered a resource, and then only when reasonable technology and economics are demonstrated. No HDR utilization technology has yet been fully demonstrated, and the economics of HDR have not been established. Hence this report cannot estimate HDR resources, rather it addresses the potential resources, the HDR resource base, or heat in the ground.

All presently exploited geothermal resources, and most of those that have been studied intensively as possible geothermal energy sources, are hydrothermal convection systems associated with geothermal systems. In these systems, most of the energy is transported by aqueous fluids. However, other types of geothermal heat exist. In particular, localized thermal anomalies exist at shallow levels in the earth's crust in which the heat is not stored by or available from <u>in situ</u> fluid-convection systems. These are the geothermal energy systems that have been designated as hot dry rock. It is frequently observed that HDR exists in association with recognized or developed hydrothermal reservoirs; witness the dry but hot holes in these fields.

Questions that arise immediately are: "how dry?", "how hot?", and "how shallow?" Additionally, it is logical to ask whether there might be any hydrothermal activity associated with hot dry rocks. Therefore, consider HDR as being crustal materials that have the following characteristics: they cannot produce an economical volume of hot water or steam; their temperature is less than about 650°C (so as to exclude molten lava or magmas); and they are located at depths less than 10 km. It is also clear that hot dry rocks may be associated at some locations and/or some depths with hydrothermal systems and/or magma.

The various types of heat sources that produce geothermal systems that may contain HDR include: (1) hot igneous systems -- most of these will be young (Quaternary) volcanism, but some might be large and older (Tertiary), others may be plutonic and not associated with volcanism, and (2) regions of above-normal heat flow, due either to a warm upper mantle or to localized radiogenic heat sources within the crust. The most readily identifiable regions within which high temperatures are likely to exist at shallow depth are those geothermal systems associated with igneous sources. In general any magma chamber will have an aureole of surrounding hot rock, which experience suggests will have low permeability. The size of the aureole might or might not be large. Furthermore, hydrothermal convection systems whose heat source is an igneous intrusion close to magmatic temperatures commonly may be underlain at some depth by hot dry rock. In areas of low or variable permeability, hydrothermal and HDR might exist in close proximity. Drilling experience in existing hydrothermal fields suggests that this is the case. Therefore, criteria for selecting favorable HDR regional sites for scientific study and resource base assessment would be geothermal systems that show: (a) evidence of youthful volcanism, especially those which might indicate large shallow magma chambers or plutons, (b) localized high heat flows in regions of high geothermal gradient or active tectonism, and (c) associated basement geology favorable for low water content or low permeability.

2.5 The Resource Base Assessment Problem

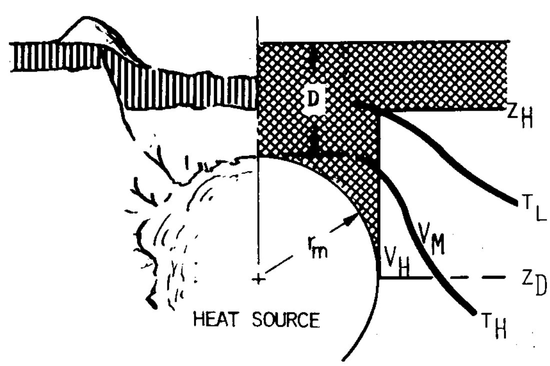
Quantitative estimates of the magnitude of the total geothermal heat contained in the earth's crust (Brown, 1973; Diment et al., 1975; Smith and Shaw, 1975) indicate that the HDR resource base is vast, far exceeding the energy contained in hydrothermal systems alone (see Table 2.5.I). HDR geothermal energy

Table 2.5.I Estimated heat content of U.S. Geothermal Energy Systems.

Resource Type	Identified	Estimated Total
Hydrothermal (<3 km)		
Vapor-Dominated (~240°C)	26	
High-Temperature Water (>150°C)	370	3×10^3
Intermediate Temperature (90° to 150°C)	345	
Igneous Related (<10 km)		
Molten (>650°C)	13,000	10^5
Hot (<650°C)	12,000	
High Regional Heat Flow (<10 km)	8,000,000	8×10^6

*All Values in Units of 10^{18} cal (8×10^6 cal is approximately equivalent to 33000 Q).

SCHEMATIC CROSS SECTION OF A SILICIC CALDERA



T_L & T_H are specific isotherms

The cross-hatched area schematically shown above (right) may be hydrologically complex and convection dominated, therefore not available as HDR.

HDR GEOTHERMAL SYSTEM MODEL $Q \sim VC_p \Delta T$

$V_M, V_H, = V(R_M, D, Z_H, Z_D, \tau)$

	Thermal Model Parameters	Principal Data Sources
R_M,	Configuration and size of magma chamber	Volume of volcanics Geophysics Petrology of volcanics
D,	Depth of burial	Geophysics Eroded analogs
τ,	Time since emplacement	Ages of volcanics
Z_H	Depth of hydrologically complex zone	Drilling experience
Z_D,	Drilling limit	$\$ \propto Z_D^3$

Others/contact relations, emplacement history, petrologic evolution through time
Permeability through time; heat transfer mechanisms

Figure 2.5.1 Factors in characterization of a HDR system associated with a shallow magma chamber.

is stored at various locations within accessible parts of the earth's crust, where "accessible" means depths reasonably reached by current or near-current drilling methods. The HDR will range from very high grade for large bodies of very hot rock near the surface, to very low-grade regions with moderate to near-normal regional geothermal gradients. Virtually all the high-grade HDR is expected to be associated with young igneous complexes, hence are localized in nature.

The first component of HDR assessment is the evaluation of various types of heat sources and determination of the heat content of an associated volume of rock. This requires defining spatial distribution of rock units, especially their physical characteristics, principally temperature, but also permeability, composition, heat capacity, density, and thermal conductivity. This implies that a quantitative mathematical model for the thermal state of a specified volume of rock and associated fluids must be developed.

The problem is schematically illustrated in Fig. 2.5.1, where the heat source for this example is a shallow magma chamber, assumed to be a sphere of radius r_m with its top at depth D below the surface. The region of interest for HDR geothermal energy assessment is the neighborhood of the magma chamber excluding the chamber itself, the region directly above it and at depth of less than Z_H (a hydrologically complex surface zone) in its vicinity (crosshatched), and above a certain accessible drilling depth Z_D. This region can be divided into high-, medium-, and low-rank geothermal zones by the isotherms T_H and T_L, the specific values of which are determined by technological considerations of extraction and utilization. A quantitative evaluation of the HDR defined here requires a knowledge of several parameters that affect the thermal evolution of the magma chamber. These parameters listed in Fig. 2.5.1 must be determined by geological and geophysical observations coupled with geochemical-petrological laboratory measurements before realistic results can be obtained from detailed calculations. All of these efforts are focused on understanding the nature of the heat source and are directed toward developing a quantitative geological model, especially for the thermal evolution of a particular region within the earth's crust. It is noteworthy that there exists much recent work on the thermal and chemical evolution of igneous intrusive systems which applies to problems of ore deposition as well as geothermal resources. The heat and mass transfer mechanisms only now are becoming well understood.

After quantitative description of the heat source, characterization of specific geothermal resources can follow. The geological and thermal evolution modeling discussed above relates to resource base assessment and focuses on natural geological processes occurring over a long period of time. Reservoir characterization will focus on those properties that influence the behavior of portions of the geothermal system under manipulation on man's engineering time scale -- generally in years or decades. Quantitative models for reservoir performance under production may include parameters not included nor necessarily required to characterize the resource base, that is, to evaluate the thermal evolution of the system prior to geothermal operations. The time scales of natural thermal and chemical diffusion and chemical reaction rates may differ by orders of magnitude for natural thermal evolution on the one hand, and artificial manipulation of the system, on the other.

White and Williams (1975) summarized the geological characteristics used by the U.S.G.S. in defining potential geothermal energy systems. Their list (Table 2.5.II) applies quite well to the problem of HDR resource base assessment.

The exploration rationale to be followed for evaluation and eventual selection of specific targets and sites for drilling includes collection and reviews of previously existing data beginning on a regional scale, progressing to more detailed geological, geophysical, and geochemical studies to be used in the construction of models for the heat source and associated geothermal systems. A typical list of exploration techniques is shown in Table 2.5.III. Experience suggests that a minimum of 2 to 3 yr of work on any particular region is required to begin modeling its heat source and possible associated geothermal resources; compilation of already existing data and collection of new data are generally required even in the initial stages; quantitative resource base characterization and assessment may require 10 to 30 man-years of effort and generally cannot be concentrated within less than about 2 yr regardless of the level of effort expended. The principal source of initial data is the U.S.G.S., although the amount, types, detail, and applicability of data will vary from site to site depending on the objectives of the scientific investigations that were carried out in the areas. A reasonable data base for an HDR assessment is listed in Table 2.5.IV.

Table 2.5.II Geological characteristics of use in geothermal system assessment and exploration.

Recent Volcanism

Hydrothermal Activity

High Heat Flow

Uplift

Earthquake Swarms

Recent Extensional Faulting

*Source: USGS Circular 726
White and Williams (1975)

Table 2.5.III Exploration techniques for geothermal system modeling.

REGIONAL GEOLOGY

GEOPHYSICAL
- GEODESY
- SEISMOLOGY-ACTIVE AND PASSIVE
- ELECTROMAGNETIC
- GRAVITY
- HEAT FLOW

GEOCHEMICAL
- PETROLOGY
- GEOCHRONOLOGY
- GEOCHEMISTRY OF HYDROTHERMAL FLUIDS
- SOIL GASES AND DIFFUSION HALOS

EXAMINATION OF ERODED ANALOGS OF MODERN GEOTHERMAL SYSTEMS

DRILLING

Table 2.5.IV Recommended uniform data base for candidate HDR sites.

SCALE/STATUS OF DATA	PURPOSE	MATERIALS	
		GEOLOGY-TOPOGRAPHY	GEOPHYSICS
1:1,000,000 DATA ALREADY EXIST IN GENERAL	ESTABLISH BROAD REGIONAL CONTEXT OF GEOLOGY-PHYSIOGRAPHY-GEOGRAPHY OF U.S.	GEOLOGIC MAP OF U.S. TECTONIC AND BASEMENT MAPS OF U.S. 1:10^6 TOPO MAPS LANDSAT (ERTS) IMAGERY	REGIONAL SEISMICITY HEAT FLOW COMPILATION (AAPG) REGIONAL AND AEROMAG
1:250,000 DATA EXIST IN GENERAL BUT MUST BE COMPILED	TO PLACE HDR RESOURCES IN GEOLOGICAL CONTEXT OF REGION, TO DEFINE LIMITS OF PROBABLE HEAT SOURCE AND RESOURCE TYPES OF A SPECIFIC AREA.	•1:250,000 TOPO SHEETS •SHADE RELIEF FROM ERTS •DIGITAL ERTS (PHOTOS) •COUNTY GEOLOGIC MAPS	AEROMAGNETIC MAPS GRAVITY MAPS MAGNETIC SOUNDING DEEP MAGNETIC SOUNDINGS DEEP SEISMIC PROFILING PASSIVE SEISMIC ARRAY GEOPHYSICAL LOGS SHALLOW HEAT FLOW
1:62,500 - 1:48,000 SOME DATA WILL EXIST BUT IN GENERAL NEW DATA MUST BE ACQUIRED	DETAILED GEOLOGY OF THE GEOTHERMAL SYSTEM; WITHIN THIS BASE. DETAILED STRUCTURE OF THE SYSTEM IS DEFINED AND THE POSSIBLE TARGETS FOR DRILLING LOCATED.	•15' TOPO SHEETS •15' GEOLOGICAL QUAD MAPS •LOW-SUN-ANGLE PHOTOGRAPHY (FAULTS)	ELECTRICAL SURVEYS SEISMIC-ACTIVE, PASSIVE HEAT FLOW MAPS GRAVITY MAPS (FOR STRUCT. DEFINITION)
1:24,000 AND SMALLER NEW DATA	DETAILED GEOLOGY OF TARGET DRILL SITES; IN GENERAL SEVERAL (2 TO 6) SPECIFIC TARGETS NESTED WITHIN AN AREA AS OUTLINED AT 1:62,500.	•TOPO SHEETS •GEOLOGIC MAPS •AERIAL PHOTOMOSAICS OR ORTHOPHOTOS •DRILLING DATA/LOGS/CORES FOR SUBSURFACE GEOLOGY (IF AVAILABLE)	ELECTRICAL CONDUCTION MAPS SEISMIC-ACTIVE, PASSIVE HEAT FLOW SLIM HOLE DRILLING

2.6 Approach to the Solution

HDR may occur in several different geological settings. To arrive at a more accurate assessment of the magnitude of the potential HDR geothermal resource, each principal type of occurrence should be characterized. Some factors of use in the selection of HDR sites representative of each major type of occurrence include (1) recent or Quaternary volcanism, (2) current or recent hydrothermal activity, (3) high regional heat flow, and (4) current or recent tectonic activity. Some examples of specific geologic settings that include one or more of the above factors are:

- large silicic calderas
- silicic dome clusters
- andesitic/silicic domes and dome clusters
- andesitic volcanoes
- basaltic volcanoes
- areas of high regional heat flow
- areas of active rifting

One rational strategy would be to characterize one of each of the major types of HDR occurrences. Characterization of each such principal HDR occurrence obviously begins with a compilation and review of all available data on the geology, geophysics, heat flow, and any existing (and available) drill hole data.

The following discussion is offered as a reasonable scenario for characterization of each such HDR system. After all the existing data for an HDR occurrence have been collected and analyzed, the collection of new surface data as required should be initiated. The situation in a given region will depend on the previous work and will be very site specific.

These new data would include:

- detailed geologic mapping and geochronology
- gravity and aeromagnetic surveys
- remote sensing surveys such as thermal IR
- electrical resistivity and electromagnetic surveys
- microearthquake and seismic noise investigations
- surface deformation studies
- seismic P-wave delay studies
- active seismologic surveying

Although shallow heat flow measurements require some drilling, they would normally be accomplished at the same time as those listed above, and are among the most important geophysical measurements to be made.

After the surface data have been acquired, reduced, and analyzed, a preliminary geological model for the geothermal system can be formulated. The preliminary model should then be tested and refined through subsurface investigations, i.e. drilling.

The primary subsurface data of interest concern the regional heat flow. A heat flow survey may consist of measurements in existing holes, extensions of existing drill holes, or the selection of one or several areas for detailed work within the regional extent of the geothermal system. The selection of the pattern of heat flow holes clearly is dependent on the geology of the system revealed by the surface survey data, the hydrology of the system, and the rock units accessible to shallow hole drilling. The resulting heat flow contour maps will aid in defining the heat source and the thermal regime at depth. Thermal anomalies can be partially characterized. These shallow hole data must be interpreted with care because elevated heat flow can be due to conductive processes or indicate a deeper convective hydrothermal system. Conversely, high heat flow regimes can be perturbed or masked (depressed) by ground water flow and near-surface hydrological conditions. With proper care, and utilizing the previous geophysical and geochemical results, the heat flow data can delineate the potential HDR and hydrothermal resources within the geothermal system. The heat flow data may also indicate the need for additional and/or more refined surface survey data. The geological models derived at this point can be used to select targets for slim hole (low cost) drilling to verify or test the resource base for the region.

Slim hole drilling at approximately 10-cm (4-in.) diameter may be used to obtain information at depths up to 1500 m (5000 ft) over a large area at minimum cost, although there is some disagreement regarding the true cost effectiveness of slim hole drilling because of hole collapse problems and limitations on borehole measurement capability. Four to six slim (or low cost) holes may be needed to characterize a regional site.

During drilling, measurements can be made of temperature, some hydrologic parameters such as ground water flow, drill bit penetration rate, torque and depth, and some other engineering parameters. These data would be useful in possible future production drilling operations. Some of these measurements might be made on the surface, by attaching sensor systems to flow lines on the rig for example, but obviously all downhole measurements must be made with a remote sonde. Most downhole logging methods developed for use in the oil and mining industries require 7.5- to 10-cm (3- to 4-in.) diameter holes, and only a few logging instruments can be used in holes less than 3.7-cm (2-1/2-in.) diameter. Most of the deep logging in slim holes needs to be done in the smaller diameter cased holes. Furthermore, few of the present logging devices are designed to withstand temperatures above 150°C; therefore, only minimum logging may be possible until higher temperature instruments designed for slim holes are available.

Slim hole drilling does allow continuous coring operations. The following physical properties and characteristics of the representative rock types in the cores can be determined: density, microstructure, pore size, shape and volume, thermal diffusivity, thermal expansion, specific heat, compressive and tensile strengths, fracture characteristics and elastic moduli. The cores can also be characterized in terms of their petrology, mineralogy, and chemistry. These data are crucial for development of a geological model for each geothermal system, to characterize the resource base, and ultimately for energy extraction models (reservoir behavior predictions).

Following the coring and logging operations these holes should be cased to within approximately 300 m (1000 ft) of total depth. This will allow determination of equilibrium temperature gradients for heat flow.

The core data, heat flow studies, and geophysical surveys can then be used in conjunction with the models derived from the previous surveys to construct a series of structure cross sections showing the distribution of physical properties through the volume surveyed. These sections can then be used to interpret and refine the earlier survey data and possibly to suggest other surveys that may be useful, particularly in defining the nature of specific structures that may be important in evaluating the various types of geothermal energy contained within the geothermal system.

Ultimately, characterization of each type of HDR occurrence will require deep drilling. It is fundamental in characterizing these HDR occurrences to identify and verify the nature of the heat source. We expect that these deep wells must be drilled to depths exceeding 3,000 m (10,000 ft) or 250°C. Minimum borehole size to allow for subsequent downhole experiments and/or production use is about 30 cm (12 in.).

During this deep drilling, coring and temperature logging would normally be performed at approximately 700-m (2000-ft) intervals or at drill bit replacement depths. Borehole logging should normally be performed before each casing string is run. Downhole geophysical logging using electrical, radioactive, acoustical, and other measurements should be made in order to obtain as much information as possible about the porosity, permeability, textures and structures, discontinuities, fluid density and movement, lithology, and temperature gradient.

Once the nature of the heat source is verified and a satisfactory characterization of the geothermal heat is accomplished, the HDR portion of the heat may be further investigated by conducting fracturing or heat-extraction experiments. Both system characterization and experiments should be performed not only to gain detailed knowledge of the system but also with the immediate practical objectives of answering questions regarding future extraction technology development and the utilization of the potential resource.

A systematic resource base assessment and characterization program of the type outlined above has not yet been carried out for any geothermal system. The two geothermal systems, Valles Caldera and Marysville, previously explored for possible HDR resources, have not yet been subjected to such a systematic investigation. The program under way at the Coso Area, however, does aim at an assessment of the different forms of geothermal energy present, as well as contributing to the development of techniques and strategy of characterizing them.

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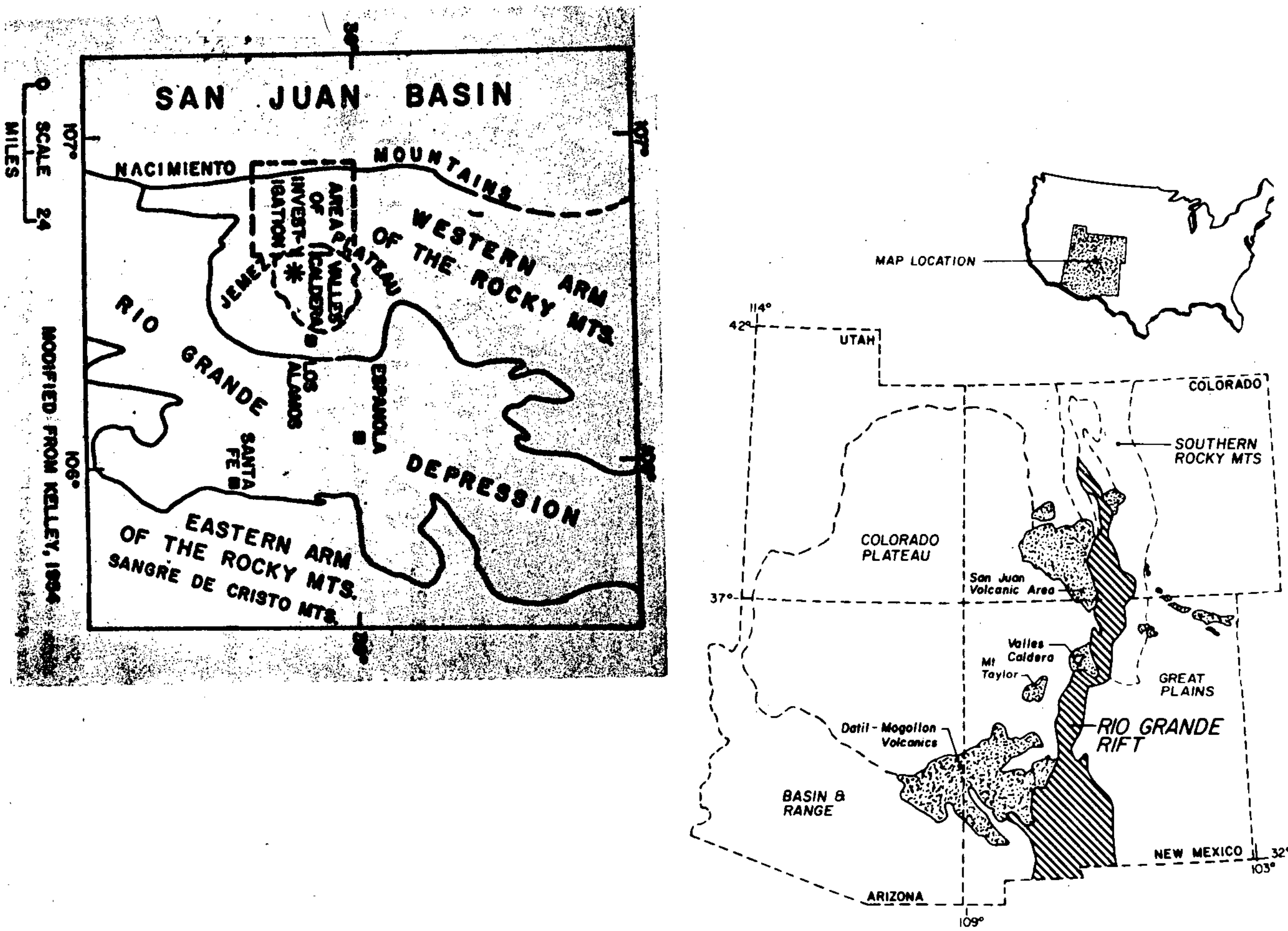
3. HDR - CASE HISTORIES

This section contains brief summaries of the exploration activities, regional survey results, and subsurface drilling performed at the three sites so far explored for HDR purposes. Each of these three localities: Fenton Hill (associated with the Valles Caldera, NM geothermal system), Marysville (associated with the Marysville, MT thermal anomaly), and Coso Area (related to the geothermal system of the Coso Mountains, CA), was chosen initially with different objectives in mind and is in a different stage of investigation. The following summaries for these three investigations contain a historical sketch of initial exploration, objectives, and criteria used in selecting the localities, surface survey and subsurface drilling results, and the current status of knowledge.

3.1 Fenton Hill

Introduction. The area selected by the Los Alamos Scientific Laboratory (LASL) for the location of Geothermal Test Hole No. 2 (GT-2) and the first borehole of the energy extraction system (EE-1) is on Fenton Hill, within the Jemez Mountains, Sandoval County, NM, (Fig. 3.1.1). It is located on the western flank of the Valles Caldera about 32 km west of the city of Los Alamos, with access provided by New Mexico Highway 126. The area lies within a large burned-over area on U.S. Forest Service land where the environmental impact of drilling has been minimal. In terms of regional geologic setting, the Valles Caldera is one of a series of large, young (Tertiary) silicic volcanic complexes occurring along the western margin of the Rio Grande rift, (which is now believed to be among the major extensional continental rifts of the earth).

The selection of Fenton Hill was unique in the sense that the goal of LASL, as originators of the hydraulic fracture concept for HDR geothermal energy extraction, was to locate a test site where the extraction method could be tested and demonstrated. Location of impermeable rock suitable for an experimental program to test the feasibility of the extraction technology was of primary importance. In no way was the Fenton Hill selection program established as an attempt to evaluate the HDR resource base associated with the Valles Caldera geothermal system nor will this one area suffice to evaluate or characterize all HDR. At the time the Jemez Mountain region was selected no formal geothermal energy project existed at LASL, and evaluation of regional and areal



The Rio Grande Rift

Figure 3.1.1 Index map of major structural features and location of the area of investigation for the Fenton Hill site in north-central New Mexico. Dot indicates location of drill holes GT-2 and EE-1 and star indicates hydrothermal development by commercial interests.

geology for targeting a drill site was done by volunteers in the evenings and on weekends. This limited the area that could be evaluated to one near Los Alamos. In addition, only limited funding was available for regional evaluation and collection of new data. Because of these last two constraints, considerable reliance was placed on published maps and reports, and on open-file maps and reports made available by the U.S.G.S.

Despite the unique purpose anticipated for the Fenton Hill area, its selection and evaluation proceeded logically in a series of phases or steps. The first phase consisted of the selection of a suitable region and the

Bailey, Cordell, and Slemmons contributed unpublished data that greatly aided in selection of the first drill site.

As stated previously, the area available for evaluation by project personnel was restricted because of shortages of manpower and funding. Fortunately, LASL is situated on the eastern flank of the Valles Caldera, one of the youngest large calderas in the U.S., a recognized geothermal system, and a designated known geothermal resource area (KGRA) by the U.S.G.S. An excellent geologic map and an interpretative cross section of the caldera, Smith, Bailey, and Ross (1970), (Fig. 3.1.2), indicate that a magma chamber or pluton probably exists beneath the caldera. Their cross section shows a diameter for the pluton approximately equal to the diameter of the caldera ring faults, i.e., about 24 km. The volcanic activity that produced the caldera occurred in two episodes, 1.4 to 1.1 m.y. ago (Doell et al., 1968), and the youngest dated volcanism in the area occurred less than 0.043 m.y. ago. The youth, magnitude, and duration of activity suggested that a local heat source was still available beneath the caldera. Supporting this conclusion is the presence of numerous hot springs within and adjacent to the caldera (Smith et al., 1970). The Valles Caldera is obviously a major geothermal system.

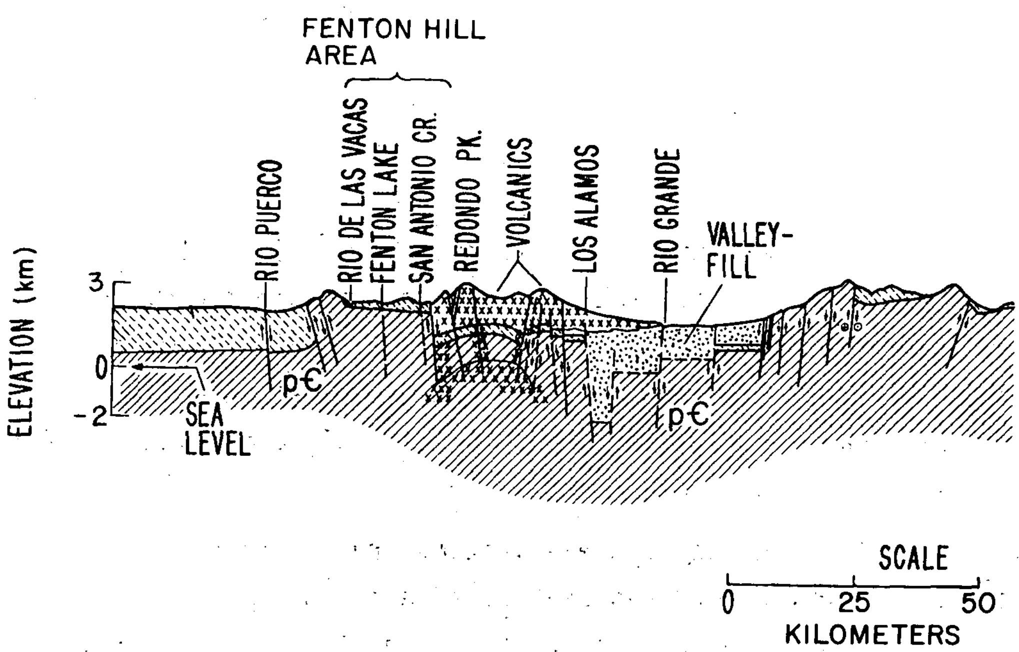


Figure 3.1.2 Generalized geological cross section of the Valles Caldera. Inclined solid lines: Precambrian undivided; inclined dashed lines: Paleozoic and Mesozoic sedimentary rocks; Dots: Santa Fe Group; Crosses: Volcanic and inferred plutonic rocks of the Jemez Mountains.

collection and assessment of available data for that region. During the second stage, new data were collected and evaluated, narrowing the region to the west side of the caldera. In the third phase, a slim hole was drilled into the Precambrian basement rocks, confirming that the western side of the caldera contained potential HDR. At the end of the third phase, the Fenton Hill area was selected for deeper drilling and as a test site for the hydraulic fracture and energy extraction experiments. The investigations at Fenton Hill are now in the fourth stage, developing and testing of the energy extraction technology. Before the results of the work done within each of these phases are discussed, a brief historical background and statement of the rationale used in targeting the drill site is presented.

Historical Background and Region Selection Rationale. In 1971, several LASL staff members (Robinson et al., 1971) conceived the HDR geothermal energy extraction concept, and the search began for a region in which to test this method. The intent of the exploration was to provide a drill site at which to develop a method for extracting geothermal energy that was broadly applicable, particularly in regions where natural hydrothermal resources are lacking, or in portions of geothermal systems where hydrothermal resources are known not to exist. Because the first site was intended to be used as a test of the extraction method, it was decided to minimize costs by selecting an area where adequate rock temperatures could be reached at moderate depths. M. C. Smith, in an informal report of May 1973, stated that at the first drill site, impermeable rock (less than 0.01 millidarcy) at a temperature of at least 200°C should be encountered at depths of less than 3 km. In addition, it was stated that to prevent fluid leakage to the surface, the top of the artificially generated fracture should lie at a depth below the surface at least equal to the diameter of the fracture. Environmental criteria for the drill site such as low seismic activity, minimal disturbance of land, water, and vegetation, and aesthetics were also proposed.

During all four phases of the selection and testing in the Fenton Hill area, the development effort has been advised by the LASL Geosciences Advisory Panel (GAP), consisting of noted geologists and geophysicists from universities, the U.S.G.S., and various institutions. Roy Bailey, Lindreth Cordell, and Frank Trainer of the U.S.G.S., and David B. Slemmons of the University of Nevada at Reno also served as informal advisors to the project.

At the time of the first phase of operations, preliminary drilling had been completed within the caldera by private interests in an attempt to locate natural hydrothermal resources. Newspaper accounts indicated that high temperatures and geothermal fluids had been encountered in some drill holes.

With a heat source indicated, it was then necessary to locate impermeable reservoir rocks which would lead to the selection of a drill site; i.e., determine what parts of the geothermal system might contain HDR. The geologic map and cross sections of Smith, Bailey, and Ross (1970) showed that Precambrian igneous and metamorphic rocks were exposed locally at the surface on the west side of the caldera. It was apparent from the geologic map and cross sections that areas could be found west of the caldera where the overlying Paleozoic and Cenozoic cover was less than 1 km (3,000 ft) thick. Mineralogical and textural evidence from exposures of the Precambrian rocks indicated that these rocks should be impermeable. The relative scarcity of large faults on the west side (Smith et al., 1970) also suggested that impermeable hot rock could be found there.

Thus, at the conclusion of the first phase, it seemed likely that both adequate temperatures and impermeable rock could be found associated with the Valles Caldera geothermal system, particularly on the west side of the caldera; outside the ring fracture.

Acquisition of New Data and Targeting of Drill Sites. The second phase of the site selection and evaluation consisted primarily of collecting new heat flow data near the caldera to confirm the presence of HDR. Holes were drilled and temperature measurements made in collaboration with Marshall Reiter of the New Mexico Institute of Mining and Technology.

Because the presence of numerous faults within the interior of the caldera suggested that it would be difficult to find impermeable rock in this area, heat flow measurements were confined to the area outside the ring faults. Initially, seven shallow holes were drilled around the periphery of the caldera (Fig. 3.1.3 and Table 3.1.I). These holes, which penetrated to depths of up to 30 m, indicated that the heat flow was indeed highest on the west side of the caldera. Conductive gradients in shallow heat flow holes are easily perturbed by the local hydrology; therefore, four additional holes (A, B, C, and D) were drilled to depths of 152 to 229 m to confirm the shallower heat flow results (Fig. 3.1.3). Holes A, B, and C, forming an arc 2.4 km outside the western

Table 3.1.I Heat flow on the Jemez Plateau.

Drill* Hole	Depth (m)	Heat Flow (HFU)
A	155	5.1
B	152	5.5
C	198	5.9
D	136	2.2

*See Fig. 3.1.3.

caldera ring fault, indicated high heat flow (Table 3.1.I), increasing slightly to the north. A decrease in heat flow with radial distance from the caldera was shown by Drill Hole D, where the heat flow was 2.2 HFU at a distance of 6.4 km from the ring fault. This value falls within the range (1.5 - 2.5 HFU) reported by Sass et al. (1971) for the Basin-Range Province, which may represent a background value for the Jemez Plateau area.

Because of the necessity of selecting an area where impermeable rocks could be found, considerable attention was paid to the tectonic setting of the caldera. Faulting is more common on the east side of the caldera where it overlaps the Rio Grande Rift. This area is broken by many north striking faults (Smith et al., 1970), apparently associated with the rifting. The Precambrian basement is not exposed on this side of the caldera and, because of faulting, it is assumed to be buried to a considerable depth.

Bailey and Cordell (personal communication, 1971) of the U.S.G.S. provided unpublished geological and geophysical data suggesting that the west side of the caldera is structurally simple and therefore would be better suited for the HDR extraction experiment.

Predrilling Geological Models. At the conclusion of the second phase, it was apparent that the magma chamber or pluton beneath the Valles Caldera had thermally perturbed the rocks in the immediate area. The magnitude of the perturbation decreased with radial distance from the caldera. High heat flow and higher probability of finding impermeable rock on the west side of the caldera indicated that further work was warranted in that area. To test this conclusion and to provide a borehole for initial hydraulic fracturing experiments, a deep, slim hole, GT-1, was located at a drill site in Barley Canyon (Fig. 3.1.3). It was anticipated that this hole would intersect the Precambrian basement at a depth considerably less than 1 km. The drilling and subsequent experiments and measurements composed the major portion of the third phase of the exploration efforts. The initial results of a study of faults and seismicity by D. B. Slemmons and a report on seismic activity by Sanford (1972) also became available at this time.

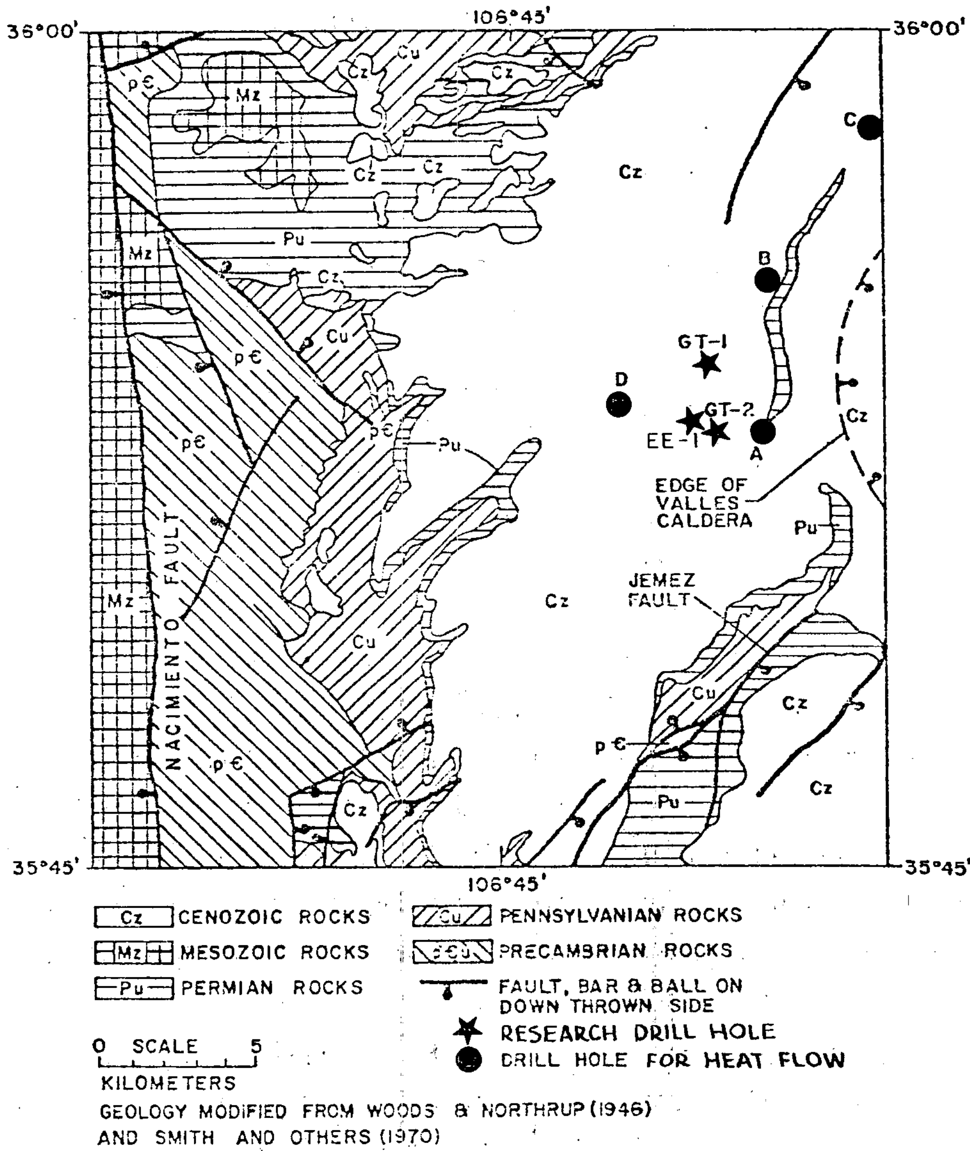


Figure 3.1.3 Geological and structural map of the Fenton Hill area with locations of heat flow boreholes (solid circles) and subsequent research drill holes (stars).

The preliminary report of Slemmons (1975) indicated that the Barley Canyon drill site and Fenton Hill area were within a large fault block bounded by the caldera ring fault to the east, the Virgin Canyon and Jemez Springs faults to the southeast, the Calaveras Canyon fault to the north, and the Rio Cibolla fault to the west. The closest of these is one of the caldera ring faults, 1.5 km east of the Fenton Hill area. The main ring fault (Smith et al., 1970) is about 3 km east of the areal site. The interior of this block is free of observable faults.

In the same report, Slemmons (1975) reviewed the seismic history of the area and concluded that it is seismically quiet. His work indicated that the seismic energy release per unit area is about an order of magnitude less than in California and Nevada. He also found that there have been no reported earthquakes with epicenters near the drill sites. Sanford (1972) also examined the seismicity in this area. From the number and strength of shocks over a 6-month recording period in 1972, he concluded that the seismicity was about one-fiftieth that of the regional average for southern California.

Slim Hole Drilling and Areal Site Confirmation. The location for GT-1 was selected on the basis of the results of the prior heat flow measurements, shallow depth of the Precambrian basement, and absence of faults in the area. GT-1 was drilled to a total depth of 785 m, intersecting the Precambrian unconformity at a depth of 642 m. Continuous coring was employed for the bottom 47 m of the hole within the crystalline rock.

After GT-1 was drilled, temperature measurements were made in the hole by LASL personnel, M. Reiter of New Mexico Tech, and A. Lachenbruch of the U.S.G.S. Agreement of results was excellent. The average gradient was 129°C/km in the Paleozoic sedimentary rocks and 45°C/km in the top of the Precambrian rocks. An abrupt change in gradients occurs in the lower Madera Limestone near the contact with the underlying Sandia Formation. This is undoubtedly due to the movement of warm water through the permeable limestone downdip away from the caldera.

The expected impermeablity of the resource rocks was confirmed by a variety of direct and indirect evidence. *In situ* permeability measurements made in GT-1 gave values of 5×10^{-8} to 6×10^{-3} darcys for overpressures of 13 to 177 bars. Eight successful hydraulic fracturing experiments at pressures of approximately 100 bars also indicated that the rocks were impermeable.

Indirect evidence for impermeable rock was obtained from the petrographic study of GT-1 cores by Perkins (1973). She found that most of the core consisted of granitic gneisses with minor amphibolite content. Although fractures were common in the core, they were almost invariably sealed by calcite or chlorite.

Refined Geological Models. At the completion of the third phase and before the commencement of the drilling of the deep boreholes, GT-2 and EE-1, it was possible to postulate a refined model for the Fenton Hill area. The heat source is provided by a pluton or magma chamber beneath the Valles Caldera with a diameter approximately equal to the caldera diameter. This heat source had locally perturbed an already high geothermal gradient providing temperature sufficiently high for the proposed experiments.

Mapping of fault locations indicated that the proposed site lies within a large block of crystalline rock that is free of any faults with surface expression. This information, in addition to the evidence that most fractures in the Precambrian rocks were sealed, suggested that low permeability rocks could be found within the Precambrian section. Slim hole drilling of GT-1 indicated that the basement rocks would be encountered at a depth of about 640 m.

Deep Drilling, Data Analysis, and Model Evaluation. The fourth phase of operations began in February 1974 with the drilling of GT-2 and has continued through the drilling of EE-1, the hydraulic fracturing experiments, and the current circulation experiments. The work at Fenton Hill is still in the fourth phase of operations, and this section is a status report as of November, 1976. A much more detailed summary has been prepared by Blair et al. (1976). The drill site was selected for GT-2 and EE-1 with the belief that it was geologically similar to the GT-1 site but better situated logistically.

GT-2 penetrated to a depth of 2,929 m, and the drilling of EE-1 is temporarily halted at a depth of 3,064 m while hydraulic fracturing and circulation experiments are being conducted. At the surface, the two holes are separated by a distance of 76.8 m. Casing has been placed in GT-2 to a depth of 773 m and a 20-cm-diameter, 185-m-long steel liner was cemented in place from 2,735 to 2,920 m. A temporary liner was placed in GT-2 from 1,917 to 1,982 m for hydraulic fracturing experiments. In EE-1, casing extends from the surface to a depth of 2,926 m and is cemented over approximately 300 m of the bottom section.

Eight hydraulic fractures were produced in GT-2, two in the open hole below the temporary liner and the permanent liner and six through perforations in the temporary liner. Open-hole fractures were made in the interval 1,977 to 2,036 m and at a depth of 2,926 m. In EE-1, open-hole fractures were created at depths of 1,976 and 2,951 m.

After the fracture at 2,926 m in GT-2 was created, EE-1 was directionally drilled to intersect this fracture. On October 14, 1975, a high-impedance connection was established between the two holes. Since that date a series of circulation experiments have been conducted to develop an understanding of the nature of the connected system.

These fourth-phase operations have provided direct evidence of the geothermal gradient and conditions at depth at the Fenton Hill site. The results of a number of related downhole experiments, studies on returned cores, and theoretical investigations were presented at a special session of the American Geophysical Union, Spring Meeting in 1976. These are listed in the reference section; the results discussed in the following paragraphs are drawn from these and other work. Nine individual temperature measurements and several continuous temperature logs made during breaks in the drilling of GT-2 indicate an average gradient of 54°C/km in the Precambrian rocks, increasing from 50°C/km in the interval 1.2 to 2.1 km to 60°C/km in the interval 2.1 to 2.9 km (Table 3.1.II and Fig. 3.1.4, Albright, 1975). The bottomhole temperature in GT-2 is 197°C and, at the present depth of 3,064 m, the temperature in EE-1 is 205.5°C.

Indirect evidence of the effects of the heat source was obtained from the results of K-Ar and fission-track dating of core samples. Argon retention in minerals is temperature-time dependent, with argon loss increasing with increasing temperature as a result of volume diffusion. The 1.7×10^9-year-old (Rb-Sr whole rock isochron) Precambrian rocks in GT-2 apparently underwent a thermal perturbation 1.4×10^9 yr ago that totally degassed argon from the minerals, resetting the clock at 1.4×10^9 yr. At 2.61 and 2.90 km, however, these rocks gave indicated K-Ar ages of 1.31×10^9 and 1.25×10^9 yr, respectively. These lowered ages reflect partial degassing associated with the present high subsurface temperatures. Because degassing has been incomplete, it will be possible, knowing diffusion coefficients of Ar, to determine when the second perturbation occurred. At this time we can only say that because

Table 3.1.II Equilibrium rock temperatures in GT-2.

Depth (m)	Equilibrium Rock Temperatures (°C)
1387	113.58
1475	117.78
1595	125.66
1670	128.35
1825	135.63
1877	138.57
1998	142.50
2040	146.20
2900	195.80
2928	197*

*Extrapolated and later measured.

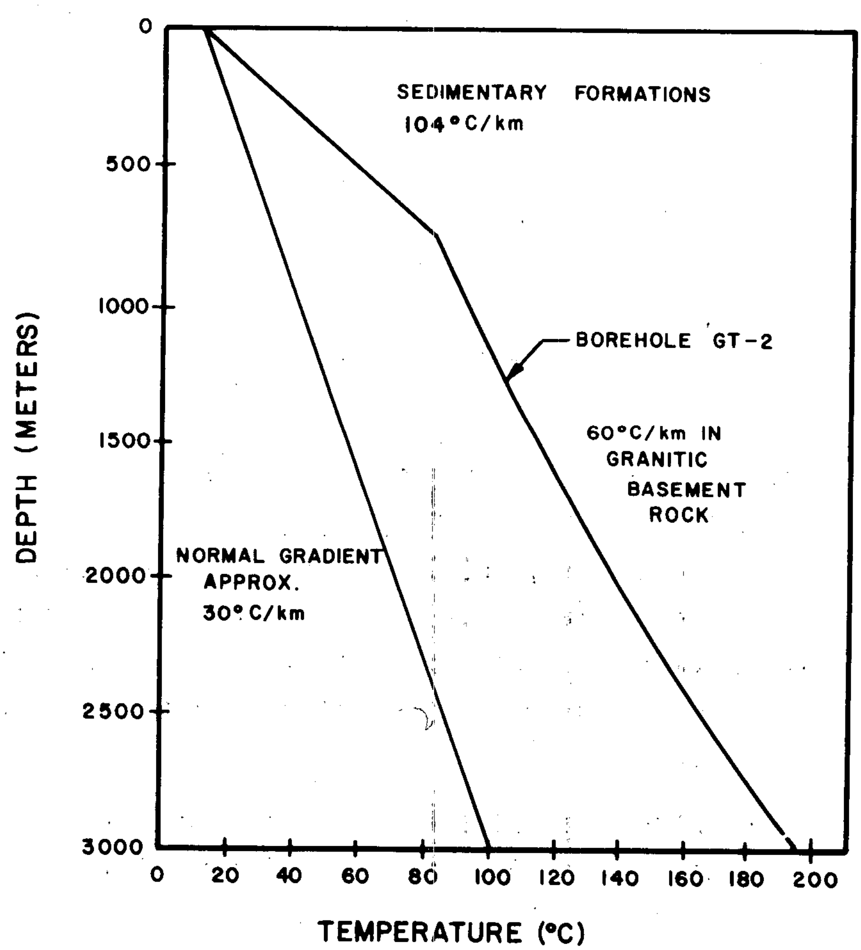


Figure 3.1.4 Thermal gradient measured in GT-2 at Fenton Hill.

present temperatures are above those where Ar loss becomes significant, at least some of the perturbation must have occurred within the last few million years.

Fission-track annealing is also a function of time and temperature. Results from measurements in the mineral apatite from core samples also indicate a very young thermal perturbation that has partially annealed the samples. In this case, a linear relationship is observed between indicated fission-track age and depth or temperature. One sample, which had fewer tracks than predicted for its depth, indicating an increased temperature, was located where a fracture zone yielded hot water that further annealed this particular sample.

Uranium, thorium, and potassium determinations from the commercially run spectral-gamma log provide data for the calculation of heat production in the basement rocks. The average values for uranium, thorium, and potassium were 4.82 ppm, 7.31 ppm, and 2.63%, respectively, values which lead to a heat production of 4.86×10^{-7} μ cal/cm^3 sec. Direct measurement of uranium, thorium, and potassium concentrations lead to a value for the heat production of 5.47×10^{-7} μ cal/cm^3 sec. If the thickness for the heat-producing crustal layer is assumed to be 9.4 km and the reduced heat flow is assumed to be 1.4 HFU (Roy, 1968), then the heat flow at GT-2 should be 1.86 to 1.91 HFU. Because the measured heat flow in GT-2 is approximately 3.7 HFU, about one-half of the heat flux is inferred to be contributed by non-steady state sources, namely the caldera and possibly heat sources within the Rio Grande Rift.

Permeability measurements have been made at the appropriate temperatures and pressures on core samples from GT-2 and <u>in situ</u> in GT-2. The core measurements were made at room temperature, 100°C, and 200°C, at a pressure of 340 bars (5000 psi). The data taken at 200°C, which corresponds to GT-2 bottom-hole temperature, gave a result of 1.2×10^{-8} darcys. The <u>in situ</u> measurements in GT-2 made over intervals of about 130 m gave values ranging from 0.3×10^{-6} to 1.3×10^{-3} darcys.

Petrographic examination of samples from 25 cores indicates that the bulk of the Precambrian terrain consists of granitic gneisses with minor amounts of mafic schist grading into amphibolite. Intrusive into the complex are two igneous rocks. A leucocratic monzogranite occurs as two 15-m-thick dikes, and a biotite granodiorite is present in the bottom 360 m of GT-2. The metamorphic rocks are moderately to strongly foliated and, in general, show abrupt variations in chemical composition. The igneous rocks are slightly foliated to unfoliated and are chemically and mineralogically homogenous. The low porosity observed in thin sections of both groups of rocks indicates that they should be extremely impermeable if unfractured.

All the cores show evidence of fracturing on several size scales, but the fractures are almost invariably sealed or healed. Calcite, which on the basis of Sr isotopic evidence is locally derived, is the most common sealing mineral. Chlorite, clays, quartz, epidote, and sulfides more rarely seal the fractures. Microfractures are often healed by the same mineral through which the fracture passes. The largest sealed fracture was about 1 cm in width, and from this maxima the fractures range down in size to microscopic. Spacing between macrofractures is also variable, ranging from about 8 cm to less than 1 cm.

Most of the thin sections examined show moderate to intense alteration of the constituent minerals. Plagioclase is the mineral most susceptible to alteration, and most grains show some alteration to sericite. Biotite may show some alteration to chlorite. Microcline is usually unaltered. In thin sections it is apparent that the alteration is fracture controlled. Because this natural alteration may closely approximate the results produced when water is artificially passed through these rocks, it is receiving considerable attention.

All of the petrographic work indicates that the Precambrian rocks at Fenton Hill should be impermeable. The biotite granodiorite encountered in the bottom of GT-2 is particularly well suited for the heat extraction experiments because of its homogeneity and tightly sealed fractures.

The hydraulic fracturing experiments in GT-2 also furnish direct evidence that the reservoir rocks at Fenton Hill are sufficiently impermeable to provide a test of the LASL HDR extraction technique.

During the fourth phase of operations, G. Jiracek of the University of New Mexico has been engaged in a resistivity study of the Fenton Hill HDR area. This project has been supported by NSF/RANN. The objectives of this electrical resistivity project are: (1) resistivity reconnaissance surrounding the LASL HDR drill site, (2) attempts to detect and define the manmade downhole fractures using resistivity techniques, and (3) development of new interpretation techniques such as generalized inversion. Preliminary results (Jiracek, 1976) indicate that the Fenton Hill site is laterally heterogeneous. A sharp lateral discontinuity trending northeast and located east of the Fenton Hill drill site probably represents the western ring fault boundary of the Valles Caldera.

The problem of assessing the geothermal resource base of the Valles Caldera complex has not been addressed directly. Clearly, potential hydrothermal and HDR resources both exist; magmatic heat probably exists at greater depths. Part of the required data for at least preliminary resource base models exist, but only part. These models could be very effectively developed in a cooperative mode between the U.S.G.S., LASL, and the commercial interests, while the HDR extraction experiment and commercial hydrothermal development proceed.

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(1) M. C. Smith, "The LASL Dry Hot Rock Concept."

(2) F. G. West and W. D. Purtymun, "Geology of the LASL Fenton Hill Site."

(3) D. W. Brown, "Recent Advances in the Deep Drilling of Hot Crystalline Rocks."

(4) R. A. Aamodt, "Hydraulic Fracturing in and Communication Between Two Adjacent Wellbores."

(5) R. M. Potter, "Characteristics of Seismic Events Associated with Hydraulic Fracturing."

(6) J. N. Albright, "Preliminary Seismic Mapping of the Main Fracture in GT-2."

(7) P. R. Kintzinger, "Geophysical Measurements at Fenton Hill."

(8) H. D. Murphy, "Extracting Energy from Hydraulically-Fractured Geothermal Reservoirs."

(9) C. Kolstad, T. McGetchin, and A. W. Laughlin, "Pluton Thermal Evolution Modeling and Observations in GT-2."

(10) A. W. Laughlin and A. C. Eddy, "Petrography and Geochemistry of Precambrian Core Samples from GT-2 and EE-1."

(11) S. B. Helmick, D. G. Brookins, J. P. Balagna, and J. Husler, "Trace Element Analyses of Granite Cores from LASL Dry Hot Rock Experiment."

(12) D. G. Brookins and A. W. Laughlin, "Rubidium-Strontium Geochronologic Study of GT-1 and GT-2 Whole Rocks."

(13) D. G. Brookins and A. W. Laughlin, "High 87/86 Strontium Ratios in Deep-Seated Fracture-Filling Calcite from GT-2."

(14) D. L. Turner and R. B. Forbes, "K-Ar Studies in Two Deep Basement Drill Holes: A New Geologic Estimate of Argon Blocking Temperature for Biotite."

(15) C. W. Naeser and R. B. Forbes, "Variation of Fission Track Ages with Depth in Two Deep Drill Holes."

(16) Colin Barker, "Gas Content of Quartz from the GT-2 Geothermal Test Hole, Fenton Hill, NM."

(17) Gene Simmons and Andrea C. Eddy, "Microcracks in GT-2 Core."

(18) J. M. Potter, J. P. Balagna, and R. W. Charles, "Permeability of a Biotite Monzogranite at Elevated Temperatures."

(19) R. W. Charles and C. C. Herrick, "Attempts to Correlate Experimental Observations with Computer Modeling for the Prediction of Mass Transport in Some Feldspar Systems."

3.2 The Marysville Anomaly

Introduction. The site for the Marysville geothermal project was selected by Battelle NW Laboratory primarily to test the hypothesis that molten rock existed within a few kilometers of the surface. Site selection was based primarily on the results of 15 relatively shallow heat flow boreholes that had been investigated by D. D. Blackwell (1969). Apparent heat flow determinations obtained in these shallow holes ranged from 3.1 to 19.5 HFU, indicating a significant thermal anomaly. If the observed high heat flows resulted from conductive heat flux from a shallow igneous heat source to the surface, would be implied, a significant quantity of HDR at shallow depths would be implied. The nonuniqueness of this interpretation was recognized by all the workers involved, especially the possibility that the thermal anomaly was hydrothermal in origin; nonetheless it was felt that the possibility of a hot igneous origin was equally viable. The initial phase of the work consisted essentially of the collection and assessment of the heat flow data. During the second stage in 1973 and 1974, new geological and geophysical surveys were made and evaluated to allow for development of a predrilling geological model and the selection of a deep borehole drill site. The third stage consisted of drilling a deep production well to a depth of 2070 m, coring and geophysical logging the well, supporting scientific studies, and data analysis. The deep well penetrated an extensive hydrothermal zone of about 93°C water that was essentially isothermal from 610 m to 2070 m. Hence, the hypothesis that molten magma (and abundant HDR) exists at shallow depth proved to be incorrect. Scientific studies of the geothermal anomaly will continue, but commercial development does not appear feasible at these low temperatures. In particular, the nature of the heat source at depth is yet undetermined.

Historical Background and Region Selection Rationale. The historic gold mining town of Marysville is located approximately 30 km northwest of Helena, the capital of Montana (see Fig. 3.2.1). Many of Marysville's old buildings remain from its gold mining days, and evidence of the mining activity is prevalent. The geothermal drill site selected during the Marysville project is located approximately 6.5 km west of Marysville in the Empire Valley. Although both Marysville and the drill site are at 1,615-m elevation, they are in different drainage basins and are separated by Mt. Belmont, which rises to

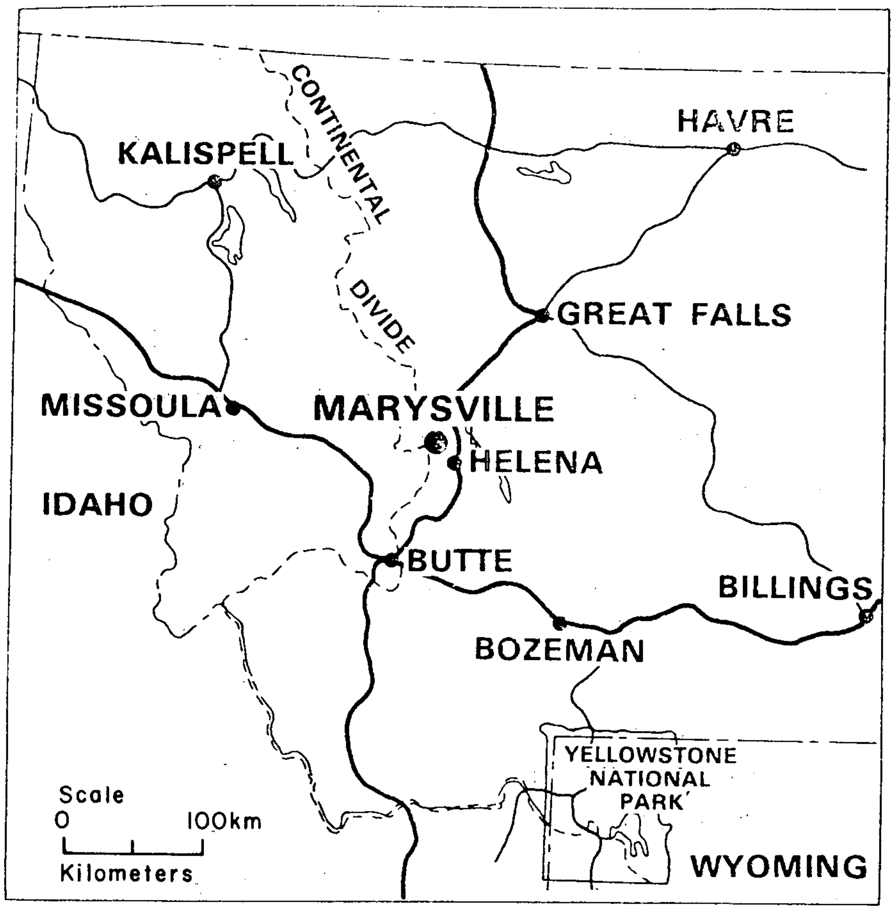

Figure 3.2.1 Location of Marysville, Montana.

2,234 m. Vegetation of the area is mostly Douglas fir, with open bunch grass regions on the south exposures and narrow stream-bottom meadows. Over 100 yr of mining operations have removed all the large virgin timber so that only second and third generation growth remains. The drill site and Marysville can be reached on good dirt roads during the summer months.

In 1969 D. D. Blackwell, while making regional heat flow measurements in the northwestern U.S. found that the heat flow near Marysville is about 10 times the regional average. These results aroused scientific interest especially because there were no surface manifestations such as young volcanics, hot springs, geysers, etc., within 30 km of the region. Further research showed that this "blind" geothermal anomaly covered a roughly elliptical region about 5 km long and 2.5 km wide in a mountainous area about 6.5 km west of Marysville, MT. One interpretation of the heat flow data was that the heat source was a granitic pluton with a volume of several cubic kilometers within about 2.5 km of the surface and perhaps as hot as 500°C. Initial resistivity measurements and other data led to the speculation that there was little water near the heat source. By any model, exploration of the geothermal anomaly was of interest to scientists. Also, there was significant economic interest in exploring the area to evaluate the heat source for its potential for generating electricity.

In the winter of 1972-73, a team of scientists and engineers assembled at Battelle-Northwest in Richland, WA, to prepare a proposal to explore the geothermal anomaly. The principal team members were from Battelle-Northwest (BNW), Southern Methodist University (SMU), and Rogers Engineering Company of San Francisco, CA. Later Systems, Science and Software of La Jolla, CA, joined the project. A proposal was submitted in February 1973 to the National Science Foundation (NSF) with BNW to be the prime contractor. The project was funded in June 1973 with Ritchie B. Coryell, NSF, as the program manager. In September 1974, David B. Lombard, NSF, became program manager. The program was transferred to the Geothermal Energy Division of ERDA in January 1975, when Lombard transferred to ERDA, until project completion in June 1975.

Acquisition of New Data and Targeting of Drill Sites. During the geological and geophysical exploration of the Marysville geothermal anomaly, all the standard exploration techniques were used, as well as several less commonly used techniques. At present, each geothermal prospect seems to require separate design of an exploration program because of the geological variability of geothermal systems; investigation of the Marysville geothermal area was no exception. The geological techniques that were used included geologic mapping, various kinds of geochemical analyses, mapping of the metamorphic mineral assemblages, and analysis of the structural geology. Geophysical techniques included two different kinds of electrical resistivity techniques (roving dipole and magnetotelluric-audiomagnetotelluric), gravity, airborne and ground magnetics, drilling for heat flow determinations, microearthquake and seismic ground noise surveys, and airborne infrared sensing.

Essentially all of the geological and geophysical techniques have furnished important data relating to the setting of and controls on the geothermal anomaly. Some of the techniques provided data more directly related to the geothermal anomaly than others, but almost all have furnished important background information for the interpretations. The uniqueness of each particular anomaly. For example, while analysis of metamorphic assemblages in rocks is not commonly included in geothermal exploration, the petrology of the metamorphic rocks was important for interpretation of the geophysical data.

A generalized summary map of the geology of the drill site area is shown in Fig. 3.2.2. The major rock units exposed include the Empire Shale, the Marysville Granodiorite, and older metamorphic rocks; the surface location of several mapped faults are indicated. Also, on this map are shown the inferred subsurface extent of the Marysville Granodiorite, the 5 HFU heat flow contour, and metamorphic isograds for tremolite and diopside. It is apparent from these data that the thermal anomaly is correlated with the outcrop of the Empire Shale, and perhaps the metamorphic isogrades not associated with Marysville Stock. It also appears that the heat flow anomaly may be founded on its

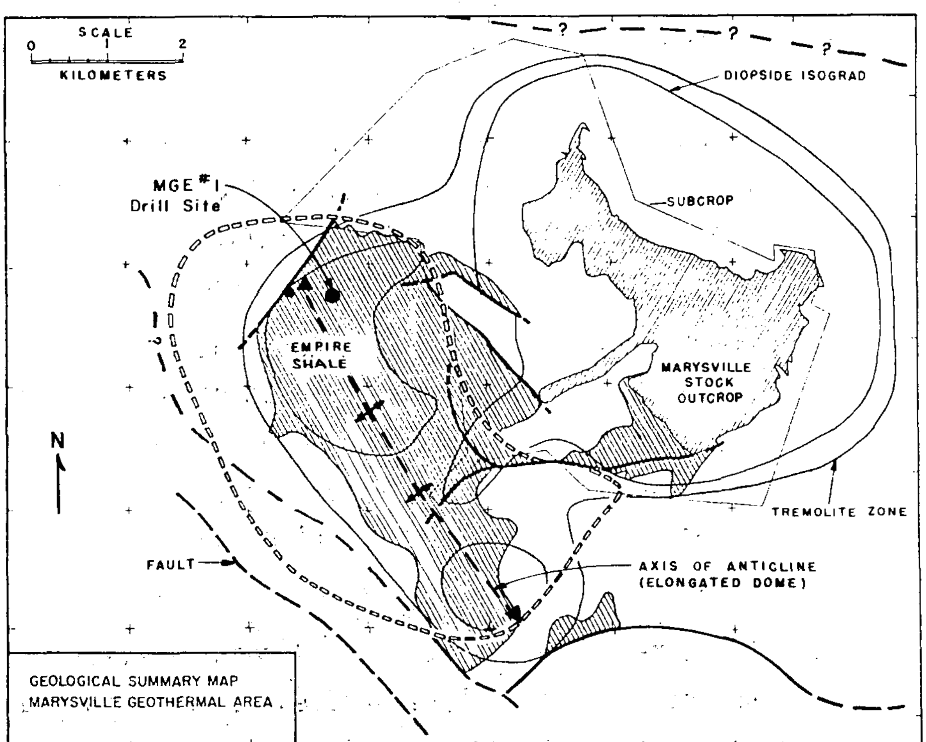

Figure 3.2.2 Summary map of geological exploration results compared to heat flow anomaly. The outcrop of the oldest unit in the area, the Empire Shale, is shown (cross-hatched); the outcrop of the Marysville Stock and the subcrop of the Marysville Stock (fine-ruled line) are also shown. Major faults are indicated by heavy lines. The tremolite and diopside contact metamorphic isograds are shown outside and inside thin lines, respectively. The 5.0-μcal/cm^{2}sec heat flow contour is shown by the interrupted double line.

northeast side by the Marysville stock. As discussed in the 1974 Battelle reports (First Annual Report, Parts I and II), the existence of isolated (high-grade) diopside-zone, contact-metamorphic rocks southwest of the Marysville Stock implies the existence of a rather large buried igneous body beneath these metamorphic zones at some time. Magnetic data preclude the existence of rock similar in magnetic susceptibility to the Marysville Stock under these zones. It is known from exploration drilling that at least parts of both of these contact metamorphic aureoles are underlain by Cenozoic quartz porphyry stocks (Rostad, 1969; Blackwell and Baag, 1973; Ratcliff, 1973). The known subsurface extent of these quartz porphyries in each area (Bald Butte and Empire Creek), before these studies, consisted of no more than a few hundred square meters, however. The correlation between the metamorphic zones and the outcrop of the Empire Shale is striking. It would appear that quartz porphyry bodies have structurally domed the Empire shale accounting for its outcrop pattern. The age of the intrusive rocks is 40 and 49 m.y., for the Empire Creek and Bald Butte Stocks, respectively. An extensive set of feldspar porphyry dikes southwest of the Marysville Stock has similar ages; one was dated by (Ratcliff, 1973) at 48 m.y. The relationship at depth between the Empire Creek and Bald Butte Stocks is still unknown.

On the basis of these relationships, the heat source responsible for the thermal anomaly was thought to be located, at least partially, in or below the Cenozoic quartz porphyries intrusions. It was clear, however, that the quartz porphyry bodies themselves could not be the source of the heat because the cooling time, even for bodies of many cubic kilometers, is on the order of 1 to 2 m.y.

Gravity, heat flow, resistivity, and ground noise surveys were conducted, and a synthesis of the results of these studies is shown in Fig. 3.2.3. The data on which these figures are based are discussed in the 1974 and 1975 reports, and reference should be made to them for detailed discussions.

In general, the geophysical data are less obviously correlated than the geological data, and their interpretation is not so straightforward. A zone of relatively high microearthquake noise lies close to the southeastern corner of the map area; two or three of the located earthquakes also fall in that vicinity. The area of the geothermal anomaly itself was aseismic, during the 5 months recorded. A residual gravity low apparently is associated with the

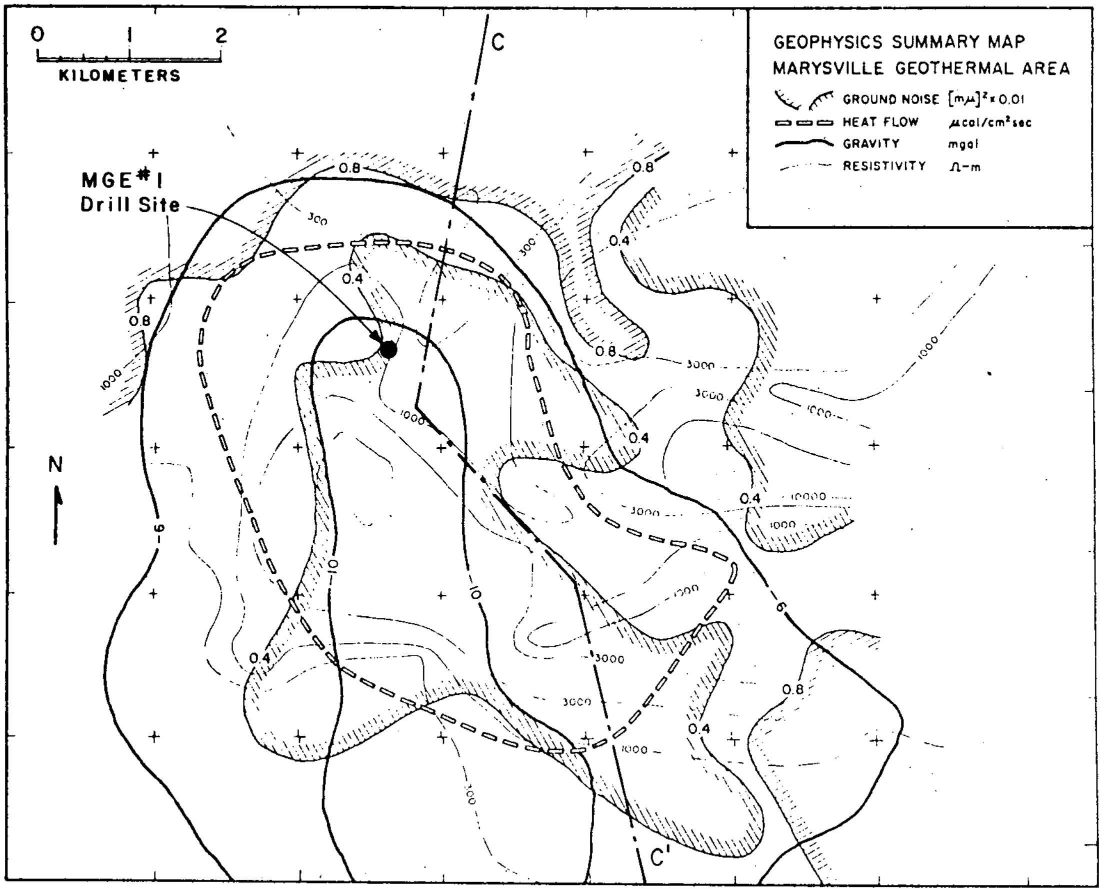

Figure 3.2.3 Summary map of geophysical exploration results. The ground noise lows and highs are indicated as are the -6 and -10-mgal residual gravity contours. The units of ground noise shown are the integral of the power density between 1 and 2 Hz (see 1974 report). The effect of the Marysville Stock has been removed from the gravity contours. One heat flow contour (5.0 μcal/cm²sec) and the apparent resistivity contours at 20 Hz are shown.

heat flow anomaly. The gravity anomaly, however, extends south off the map area, whereas the heat flow anomaly decreases markedly in amplitude to the south. The gravity anomaly could arise from mass differences not necessarily associated with either the Empire Creek Stock or the geothermal anomaly.

Electrical resistivity, in general, is one of the most valuable exploration techniques in geothermal areas because resistivity is a strong function of some of the properties most likely to vary, namely, temperature, fluid salinity, and porosity. Relatively low values of electrical resistivity are commonly associated with hydrothermal resources; however, it is clear from the previous results (Jackson, 1972; Peeples, 1975), as shown in Fig. 3.2.3, that the electrical resistivity values are very high in the geothermal area and that there is no consistent association of low resistivity with the high geothermal gradients. The roving dipole technique on which the original resistivity map was based (1974 Report; Jackson, 1972) has very shallow penetration, perhaps even as shallow as a few tens of meters, because of the extremely high resistivity of the surface rocks. To obtain deeper penetration, an audiomagnetotelluric survey was carried out. Results of that survey suggested that no significant variation in resistivity occurs until depths of many hundreds of meters (2 to 6 km) are reached. Furthermore, resistivity values were extremely high at high frequencies and rather high at the lower frequencies (minimum resistivity values were on the order of 100 ohm-m). In any event, in this particular area, the electrical resistivity data furnish little information in the depth range 0 to 2 km. However, the AMT survey clearly delineated the fault bounding the southern portion of the area, where lower resistivity shales and carbonate rocks are downfaulted against the Helena and Empire formations.

The ground noise data were different from those commonly encountered in hydrothermal areas. The lowest values of ground noise (shown in Fig. 5.2 of the 1974 report) are found in the area of the geothermal anomaly; the general values of ground noise are extremely low. Higher values of ground noise occur around the borders of the geothermal area, with the highest values found in the southeastern corner of the map. These highest values were apparently outside the heat flow anomaly, and their origin was initially somewhat unclear. However, as discussed in a subsequent section, this ground noise anomaly may indeed be related to the hydrothermal resource.

An airborne infrared survey was carried out in addition to the geophysical surveys described above (1974 Report). In general, detection of a subsurface thermal anomaly by infrared methods depends on a detectable surface manifestation; in the absence of hot springs or steam such methods are at least one to two orders of magnitude below that needed for detection of a geothermal anomaly such as the one in the Marysville area. In a mountainous area like the Marysville district the noise level from elevation, microclimatic, and vegetation effects is particularly high and furnishes the ultimate limit for the resolution of the infrared data.

Mathematical models were developed by Blackwell (1974, First Annual Report) and Hays of Systems, Science and Software (1974) assuming that the source of heat was a buried magma chamber. The models were used to simulate heat flow, and the calculated contours were compared with observed data. Depending upon the assumed shape, of the magma body, its depth of burial, and initial temperatures, excellent results were obtained between observed temperature gradients and calculated ones. However, it was noted by Blackwell and Baag (1973) and others that a convective, water-dominated system could also exist and would be consistent with observations.

Predrilling Geolgical Model. The interpretation was made that the source of the high heat flow was either a conductively cooling shallow magma chamber beneath the Empire Creek Stock, or hot ground water circulating within fracture zones in the Empire Creek Stock (Blackwell and Baag, 1973). None of the geophysical data appeared to give an unequivocal answer as to which of these two particular hypotheses should be favored. However, the consensus prior to drilling is probably best expressed in the following paragraphs taken from the First Annual Report (Blackwell et al. 1974).

> "At the present time the evidence firmly suggests that the origin of the high heat flow is ultimately a buried magma chamber. Face value interpretation of the heat flow data suggest that this magma chamber might be as shallow in depth as 1 to 1.5 km in Empire Creek, in which case the magma chamber should be penetrated during drilling of the deep hole. The estimated depth to the top of the magma chamber may be somewhat low, however. Consideration of the details of magma solidification might result in the actual depth of the magma chamber being larger than the apparent depth calculated for the model used in section 3.6.
>
> "An alternative model is that upward circulation of a small amount of fluid from the magma chamber into a fractured region above the chamber might explain the apparent shallow depth of the geothermal source body in Empire Creek. The analysis of all information seems to completely rule out the possibility of stratigraphic type reservoir or of a reservoir due to large-scale thrust faulting, and therefore the magma chamber model or some variant seems to be required to fit the data.

"If the magma chamber model is valid, then the area will have low porosity and permeability and the fluid content will probably be too small to justify economic development at the present time. However, because of the high temperatures at relatively shallow depths the area might be ideal for testing concepts for the extraction of thermal energy from hot, dry rock systems. If these types of systems can be tapped economically, then the geothermal power potential of the western United States is very large. If the high heat flow is indeed due to a cooling magma chamber and conductive heat transfer predominates, then the geothermal gradients near the surface can be extrapolated to depths of several kilometers and temperatures as high as 500°C may occur. In contrast, in geothermal areas dominated by convective heat transport, once the reservoir base temperature is reached (usually on the order of 200 to 300°C) temperatures essentially do not increase with increasing depth."

Slim Hole Drilling and Areal Site Confirmation. This phase was not included in the planning and execution of the Marysville geothermal project.

Refined Geological Models. Because no slim holes were drilled to obtain the subsurface information necessary for refinement of predrilling models, the development of refined geological models was not possible until after the deep drilling phase of the Marysville project.

Deep Drilling, Data Analysis, and Model Evaluation. Under the direction of Rogers Engineering Company, 90 days of drilling during the summer of 1974 were planned to achieve a target depth of about 1,830 m. The actual drilling of Marysville Geothermal Energy Well No. 1 (MGE #1) began on June 10 and continued until August 30, a period of 81 days, and ended at a total depth of 2,070 m. Most of the drilling was done with aerated water at rates of 5 to 8 m/hr. Two major formations were encountered. The upper formation of Empire Shale (metamorphosed shale and quartzite) extended to approximately 297 m, and the remainder of the hole was in the Empire Stock (granite porphry). There is a gradual change with depth in the Empire Stock toward a non-porphyritic granite, showing the effects of slower cooling.

The deep drilling phase showed that the Empire Stock is extensively fractured and contains a large volume of water. Water was first encountered at 465 m, and major water zones were found at 583 and 1,032 m. However, the many fractures led to speculation that the water zones are interconnected. All the fracture zones below 305 m appear to contain water. Flows greater than 16 ℓ/sec were encountered from upper fraction zones into the lower ones. Based on all the geophysical surveys that had been done at the surface, including electrical resistivity and magnetotellurics, large amounts of water had not been expected.

The hole in the upper 35 m of the well was widened to 66 cm in diameter, and casing was set and cemented to that depth. Between 35 and 404 m a 31-cm casing was set in a 44-cm hole and cemented in place. Between 404 and 1300 m a 24-cm casing was set in a 31-cm hole, but cementing was not successful and only the lower few meters of the casing were emplaced. Between 1300 m and the total depth of 2070 m a 20-cm hole was drilled and was not cased. Later a cement plug was placed in the bottom of the hole to control water flow, reducing the hole depth to 1,955 m. Although eventual plugging and abandonment is planned, the hole will remain open for scientific studies until the summer of 1976. The U.S.G.S. is now conducting regional hydrology studies and has sponsored temperature monitoring and water sampling in the well.

Schlumberger Well Services was contracted to log the well. Their first major logging was conducted to 404 m on July 7, 1974, prior to setting the middle-string casing. The second major logging, from 404 m to 2,070 m, was completed on September 10, 1974. These major loggings were to determine hole dimensions, formation resistivity, formation density and porosity, hydrogen concentration, cement bonding, natural radioactivity, fracture patterns, hole deviation from the vertical, temperature, and water flow. The results clearly show the two major formations, the Empire Shale to 297 m and the Empire Stock to depth, as well as the variations within each formation. The Shale consists of five subzones with significantly different physical properties. The Stock is quartz porphyry, which is quite highly fractured and has a bulk permeability that permits large water flow. In addition to the two major loggings, many minor loggings of temperature and water flow were made by Schlumberger and others. Although the technology exists to take adequate flow and temperature measurements at 100°C, the logging crews regularly encountered problems that made it difficult to obtain reliable data.

Core cuttings were made 18 times during drilling and produced 15 useful cores and one set of fragments. Of the 35 m cored, 25 m of useful cores were recovered. Despite the use of diamond coring bits, coring was difficult and expensive in these formations. The cores were washed, photographed, and cut for analysis. One complete set of core sections is held in archives by Southern Methodist University. The results of the core analysis show steeply dipping veins in both the Empire Shale and Empire Stock. Rock descriptions were obtained from a microscope study of the cuttings, petrographic studies of thin sections, x-ray diffraction analyses, and studies of the logs.

Rock temperature measurements were difficult because of water flow in the hole throughout the drilling operation. Generally the flow has been down the hole with the lower formations taking water from the upper ones. Flows greater than 16 ℓ /sec were encountered before setting the casing. The source of this large flow seemed to be the fracture zone between 1,032 and 1,039 m. However, flows less than 3 ℓ /sec were believed to originate from the upper parts of the hole, probably from the 583- to 590-m zone. Because the open-hole spinner test was not particularly sensitive to low flows in the large-diameter hole, accurate data above the 1,036-m level were difficult to obtain. Data obtained near the bottom of the hole indicate that most of the 16-ℓ /sec flow was going back into formation at the bottom of the hole in the fracture zone below 2,049 m. The hydrostatic pressure of this zone was apparently less than that of the upper zones, allowing the downflow of water. Whether the water flow was a local transient condition that would have stopped within a few days or a condition that might have persisted is unknown. However, the drill stem test did not show any large hydrostatic head difference between the lower zone and the upper zones.

After the casing was set and the cement plug was established in the bottom of the hole, flows were significantly reduced. Approximately 0.05 ℓ /sec was leaking through the perforations in the casing made for the second cement job, and flows immediately beneath the casing were about 0.5 ℓ /sec. Between September 10, 1974, when the packer flowmeter test was performed, and September 22, when the radioisotope test was done, an apparent equilibrium occurred in a lower part of the hole because the flow at the 1,737-m level decreased from more than 2 ℓ/sec to about 0.05 ℓ/sec. Below the 1,829-m level there is no flow at the level of detection with the isotope test. The flow test made on November 17, 1974 with radioisotope instruments showed a maximum flow of about 0.05 ℓ /sec at about 1,301 m, which had decreased to about 0.005 ℓ /sec by April 1975.

Downhole temperature measurements were made four ways: (a) Blackwell's resistance-element thermometer, which is limited to maximum depths of about 762 m and maximum temperatures of about 100°C, (b) the Schlumberger platinum resistance thermometer, (c) a Kuster downhole temperature versus time recorder, and (d) maximum-reading mercury thermometers. Generally, the data obtained by Blackwell in the upper part of the hole and the Schlumberger measurements agreed, indicating that the formation cooled as drilling proceeded. The complex structure of the temperature-depth profile presumably is caused by the inflow of water from formations before and after the setting of the casing. Logging on September 10 occurred within a few hours after most of the cool water in the mud pit had been pumped back into the hole, and consequently lower temperatures were recorded at that time. Two additional Schlumberger logs, obtained about 24 hr after the August 31 log, closely agree with those obtained on September 21. Temperatures were obtained before the casing was in place and twice afterward. Water moving down the annulus between the 24-cm casing and the hole was affecting the temperature readings in the casing. Below the casing water flows of about 0.5 ℓ/sec are sufficiently high to prevent measurement of the ambient rock temperature, and this condition generally existed down to the 1,737-m level until about November 1974. Water temperatures slightly less than 93°C were obtained throughout this entire region. Maximum temperature thermometer readings over the same region were consistently 93 to 96°C and are probably the most reliable of the measurements. The Kuster instrument was left on the bottom of the hole for 44 hr between September 19 and September 21, but it showed no temperature increase above 96°C. Because the flow rates in this region are believed to be negligible, it appears that the rock temperatures may not be much greater than 93°C.

Even in those parts of geothermal systems characterized by hydrothermal circulation, conductive heat flow measurements may be used to estimate the shape and depth of the geothermal heat if the system is capped or bounded by impermeable zones and if the temperature of the hydrothermal cell, or its depth at one point, is known. In the case of the Marysville geothermal system none of the geophysical data furnish evidence on the depth to which the temperature gradients can be extrapolated. Furthermore, there is no surface manifestation of geothermal fluid that can be analyzed geochemically and from which the estimated temperatures at depth can be calculated. However, as measured in MGE #1, at least in the northern extremity of the hydrothermal area, the base temperatures are 90 to 99°C. Based on these data an extrapolation to the depth of the 95° isotherm using the surface gradient can be made to place limits on the depth and shape of isotherms in the remainder of the system. The results of a qualitative extrapolation of the data are shown in Fig. 3.2.4.

This figure is qualitative and does not represent a mathematical solution for the isothermal surfaces. However, particularly at the northern end of the anomaly, the geometric constraints on the temperatures are strong and the reversal in temperature gradient is actually observed in MGE #1. The southern border of the geothermal anomaly as shown is much more qualitative. An approximate position of the possible 120° isotherm is also shown, based on geochemical evidence that the base temperatures in the area may be as high as 120°C. It is possible, but speculative, that drill holes on the order of 700 to 900 m deep, south of MGE #1, might encounter higher temperatures. Based on this geometric

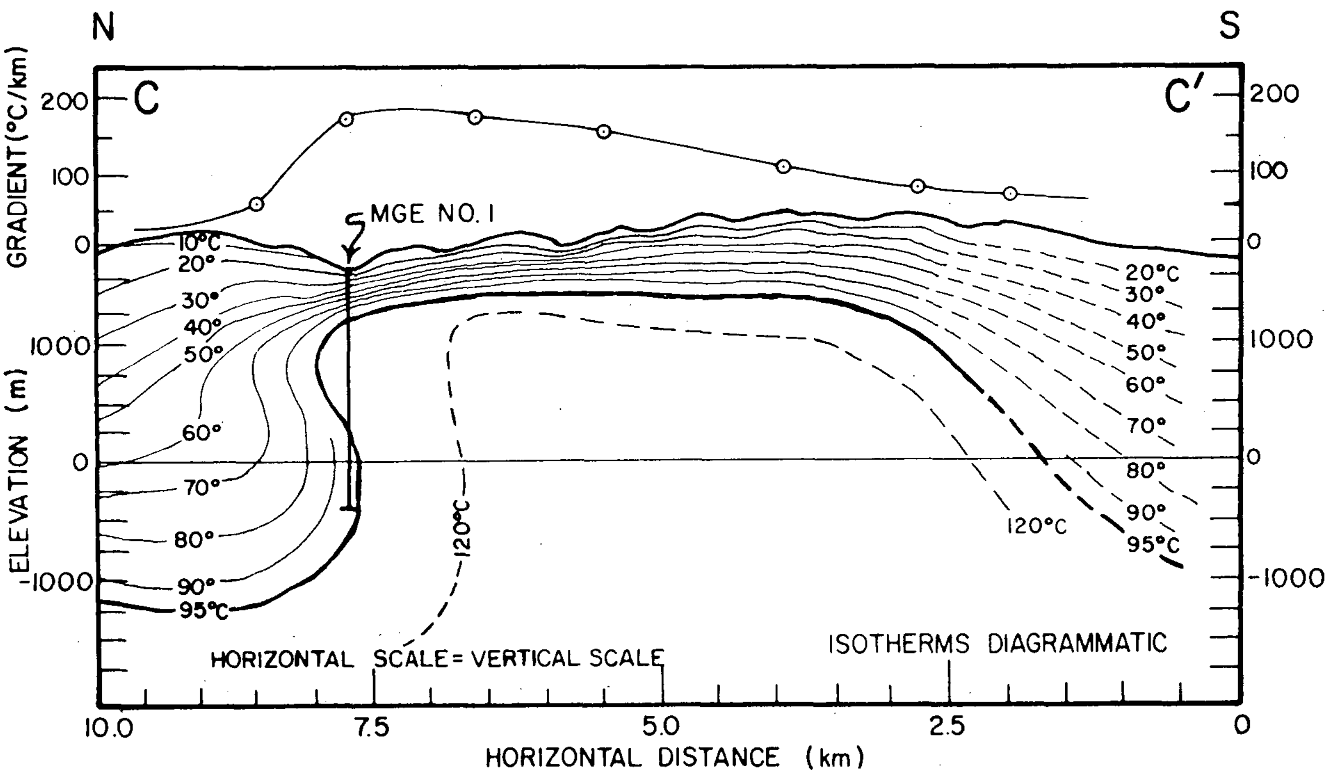

Figure 3.2.4 Cross section CC' (location shown on Fig. 3.2.3) showing inferred depths of isothermal surfaces. The geothermal gradient is shown as the top curve. The possible location of the 120° isotherm, if present at shallow depths, is shown as the dashed line. The 95° isotherm, the inferred reservoir base temperature based on the results from MGE #1, is shown as the heavy line.

construction, however, temperatures of 170 to 180°C implied by the Na-K-Ca geothermometer cannot occur over a very broad region in the geothermal area, and if such temperatures are present in the convection cell they must be confined to a thin plume somewhere in the convecting system, the location of which is now unknown.

In the previous models of the geothermal system (Blackwell et al., 1974; 1974 Report; etc.) the geometric constraints of the heat flow data were resolved by the interpretation of the source of the anomaly as a very recent shallow intrusive. In this case the time lag for heat flow through rocks allows a considerably different isothermal section than the one shown in Fig. 3.2.4 to satisfy the near-surface heat flow data that were obtained in shallow holes prior to deep drilling.

To illustrate the correlation of the geothermal anomaly with geologic structure, the observed temperature gradient and the 95°C and 120°C isotherms are shown on a geologic cross section in Fig. 3.2.5. The correlation of the highest temperature gradients with the Empire Creek Stock is clear. Also, the association of the north boundary of the anomaly with a boundary of the Marysville Granodiorite is illustrated (see Figs. 3.2.4 and 3.2.3). The apparent

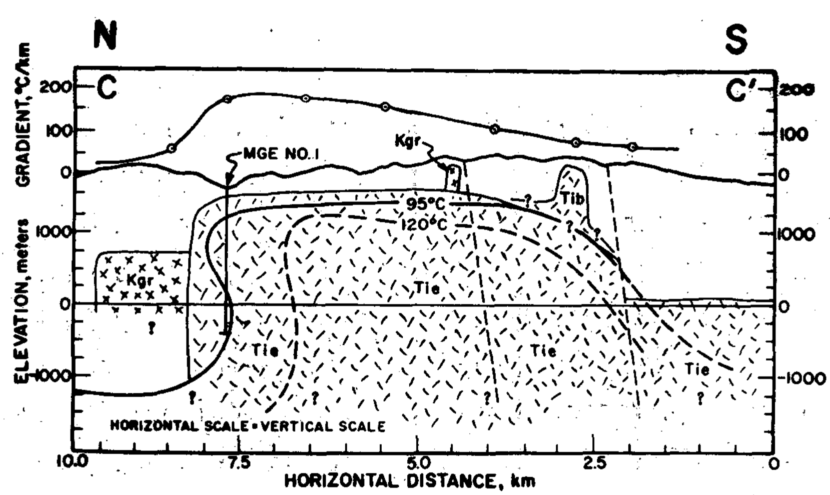

Figure 3.2.5 Geologic cross section CC' (see Fig. 3.2.3) of Marysville anomaly with 95 and 120°C isotherms superimposed.

top of the hydrothermal convection cell at an almost constant depth of 100 to 200 m below the reconstructed top of the Empire Creek Stock is consistent with either of two hypotheses for the containment of the geothermal fluids. The first hypothesis is that the highest piezometric levels reached anywhere in the anomaly correspond to an elevation of about 1,463 m, the average fluid level in MGE #1. In such a case, the fluid would not have enough pressure anywhere throughout the anomaly to reach the surface. None of the surface springs show evidence of mixing with warm water from depth, as would seem likely if the hydrothermal system is actually connected to the surface. In particular, the water from a well 100 m deep at the site of MGE #1 has fluid that cannot be derived from the geothermal fluid at 450 m by simple dilution. The second hypothesis is that the water is confined to the Stock by a relatively unfractured, chilled contact zone; thus, the Empire Creek Stock acts as both the porous host rock and its cap. This hypothesis is speculative, but seems to be consistent with the data. In either case these results seem to imply a type of hydrothermal system different from any other known. The results and implications are speculative, and confirmation can only come from further drilling and testing.

Based on the results of the surface exploration and the deep drill hole, a preliminary model of the Marysville geothermal system can be proposed, although this system appears to be unusual in several respects. Perhaps its most unusual aspect is that the host rock for hot water is a granite stock. Furthermore, it appears that circulation of these fluids is not confined to a discrete fault or fracture system, but rather is carried in a diffuse set of fractures. Secondly, it is clear that the northeast limits of the heat flow anomaly are associated with the southwest extent of the Marysville Granodiorite. Apparently one granite body (Empire Stock) is relatively permeable, whereas another adjacent one is not and acts as a boundary to the circulation system. Thirdly, no resistivity anomaly is associated with the hydrothermal anomaly even though significant hydrothermal convection is present. Finally, the heat source responsible for the hot (96°C) water found during drilling is not known but clearly cannot be the Empire Stock nor the Marysville Granodiorite, because both are much too old. A deeply buried (∿ 10 km), small, and relatively young (∿ 4 m.y.) intrusion is consistent with existing data. A systematic post-mortem on the Marysville data, including careful and systematic analysis of the cores from the viewpoint of chemical petrology, mineralogy, and geochronology, would certainly place useful quantitative constraints on the present state and evolution of the geothermal system. It is important to understand the system, to avoid similar costly drilling programs which are unproductive from a utilization viewpoint. Paradoxically, it may be true that the resource base of the deeper parts of the Marysville system is significant.

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3.3 The Coso Area

Introduction. The Coso Area has been recognized for several years as a potential geothermal resource area. Obvious surface manifestations of an anomalous concentration of geothermal energy include weak to moderate fumarolic activity, intermittently active hot springs, and associated hydrothermally altered rocks. Closely related evidence of a geothermal anomaly is provided by abundant late Cenozoic volcanic rocks, including a cluster of 37 rhyolite domes indicative of recent shallow intrusion of magma beneath the area. These geothermal features (Godwin et al. 1971) are principally what prompted the recent classfication of the Coso region as a Known Geothermal Resources Area (KGRA).

Summaries of the geology and reconnaissance geochronology of the Coso Area have been published recently (Duffield, 1975; Lanphere et al.; 1975; Duffield and Bacon, 1976). The Coso Range of southeastern California lies astride the boundary of the Sierra Nevada and Basin-Range Provinces (see Fig. 3.3.1). The area is underlain principally by Mesozoic granitic rocks that are partly veneered by late Cenozoic volcanic rocks. The volcanic units (in apparent decreasing age) include (1) widespread basaltic flows, (2) dacitic flows and tuff, and (3) rhyolitic domes and flows and basaltic cones and flows. These volcanic rocks are encompassed by an oval-shaped zone of late Cenozoic ring faulting that measures about 40 km east to west and 45 km north to south. Most of the Coso Range and a slice of the adjacent Sierra Nevada lie within this ring structure. The youngest volcanic rocks are late Pleistocene and, with associated active fumaroles, occupy a north-trending structural and topographic ridge about 18 by 10 km near the center of the ring structure.

The Pleistocene volcanic rocks (Lanphere et al. 1975) are a bimodal suite of rhyolite and basalt, which give K-Ar ages ranging from about 0.04 to 0.96 m.y., with most ages between 0.05 and 0.15 m.y. The cluster of rhyolite domes suggests a large underlying magma chamber that has periodically erupted lava to the surface during the past few hundred thousand years. Thus, a silicic magma chamber at depth is the implied heat source for the Coso geothermal system.

Historical Background and Region Selection Rationale. Before 1974, no well-funded, comprehensive scientific study of the Coso area existed, but several investigations were made as time and money permitted. Interest naturally focused on the rhyolite dome field in the center of the Coso Range, because of the obvious geothermal potential of this area.

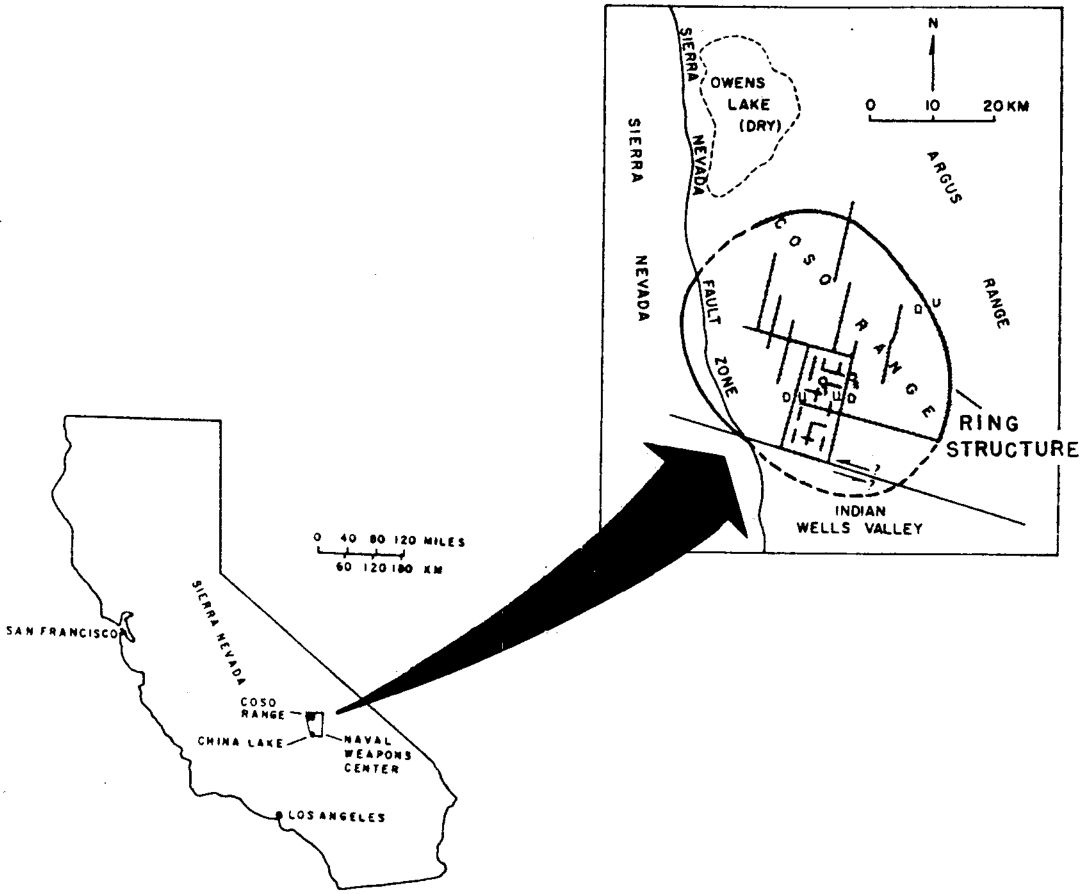

Figure 3.3.1 Index map of California showing the location of the Coso geothermal system. The more detailed map shows faults in the Coso Range area. Broad zones of arcuate faults are generalized as a single heavy line. Pleistocene volcanic rocks occur mostly within a highly faulted structural ridge in central and southern parts of the ring structure. (After Duffield, 1975).

Although geothermal activity in the form of fumaroles and hot springs has been known in the Coso area for many years (Frazer et al., 1943), the geothermal manifestations were not studied in detail until the late 1960's (Austin and Pringle, 1970). Austin and Pringle's report summarizes a combination of field geological reconnaissance, photogeology, theoretical petrology, gravity and magnetometer measurements, and mineralogical investigations that culminated in

1967 with the drilling of the Coso #1 drill hole into a fault zone along which the fumaroles and hot springs are localized at Coso Hot Springs. The hole was drilled to 114 m and has a maximum temperature of 142°C. In addition, Austin and Pringle (1970) studied the chemistry of some of the geothermal fluids, identified many secondary minerals in areas of acid-sulfate fumarolic alteration, and have begun field experiments to test the corrosion effects of geothermal steam on various pipe materials. Koenig et al. (1972) examined patterns of snow melt and infrared imagery of the area and were able to delineate surficial thermal anomalies, hydrothermally altered ground, and associated faulting. Furgerson (1973) mapped electrical resistivity in part of the area and found relatively conductive zones near fumaroles.

A seismic ground noise survey by Teledyne Geotech (1972) identified high noise levels in the immediate area of the Coso Hot Springs, near the Devils Kitchen fumarolic area, and in an area without surface thermal manifestations about 2.5 km northwest of Devils Kitchen.

Austin et al. (1971) recognized the significance of the late Cenozoic silicic volcanism in the Coso Area and suggested the presence of an underlying magmatic heat source to provide energy for the geothermal phenomena at the surface. Chapman et al. (1973) interpreted negative gravity anomalies in the geothermal area as possibly resulting from the youthful intrusion of underlying magma, consistent with the model suggested by Austin et al. (1971). The later summaries of Duffield (1975) and Lanphere et al. (1975) support this view.

Other work in the Coso area includes a petrologic investigation of the volcanic rocks by Babcock (Babcock and Wise, 1973; Babcock, 1975) in which the bimodal basalt-rhyolite is thought not to be comagmatic, with the basaltic rocks having a possible deep (mantle) origin. Also, geological training exercises were held in the Coso Range for several Apollo crews prior to lunar landings (Jackson et al., in preparation, U.S.G.S.).

Region Selection with Compilation and Review of Available Data. As already indicated, many investigators were aware that the Coso Range probably contained a significant potential geothermal resource, because of copious young volcanism, fumaroles, and hot springs (Godwin et al., 1971). The inferrence that a young silicic-magma chamber at some depth was the heat source responsible for the geothermal activity was drawn by early workers (e.g., Austin et al., 1971) and supported by later work (Koenig et al., 1972; Furgerson, 1973; Chapman et al., 1973). Smith and Shaw (1975) recognized the Coso area for its possible geothermal resources, stored in the form of magma or possible HDR.

Recommendation by HDRAP, which lead to the selection of the present area by ERDA for HDR exploration, was based largely on results of the pre-1974 studies in conjunction with available preliminary results of the more recent investigations, principally the geologic mapping (Duffield, 1975) and heat flow data (Combs, 1975) (see Fig. 3.3.2).

New Data Acquisition and Targeting of Drill Sites. In the fall of 1974, intensive study of the area was begun, including (1) geologic mapping, (2) geochemistry of the late Cenozoic volcanic rocks, (3) geochronology of the late Cenozoic volcanic rocks, (4) geochemistry of geothermal fluids, (5) further study of gravity, (6) aeromagnetics, (7) additional shallow heat flow determinations, (8) active and passive seismic investigations, (9) patterns of arrival times for teleseism, (10) first-order leveling, (11) geodimeter trilateration, and (12) additional geoelectric and electromagnetic surveys. These investigations involve personnel of the U.S.G.S., Battelle Pacific Northwest Laboratories (PNL), China Lake Naval Weapons Center (NWC), and the University of Texas at Dallas (UTD).

Geologic mapping by Duffield (1975) and Duffield and Bacon (1976) has shown that the youngest volcanic rocks and associated fumaroles lie at the center of a 50-km-wide ring fault structure that is superimposed on regional fault patterns (see Figs. 3.3.1 and 3.3.2). Duffield (1975) believes that the rhyolite dome field near the center of the ring structure overlies a young silicic-magma chamber which is responsible for the observed thermal anomaly. This is generally consistent with the model proposed earlier by Austin et al. (1971). Geochronologic studies by Lanphere and coworkers (1975) indicate that the youngest volcanic rocks are clustered near the center of the ring fault structure. The youngest K-Ar age determined on the rhyolite domes was 41,000 $\pm$ 21,000 yr B.P. for Sugarloaf Mountain, which is located at the virtual center of the ring fault structure, the center of the silicic dome field, and is adjacent to Devils Kitchen, one of the major fumarolic areas. Combs (1975) found that heat flow (Figs. 3.3.2 and 3.3.3) is generally high throughout the dome field, with values ranging from about 2 to 18 HFU, all greater than the worldwide average of about 1.5 HFU. The highest values of heat flow occur near Sugarloaf Mountain. Seismic noise (Teledyne Geotech, 1972), electrical resistivity lows (Furgerson,

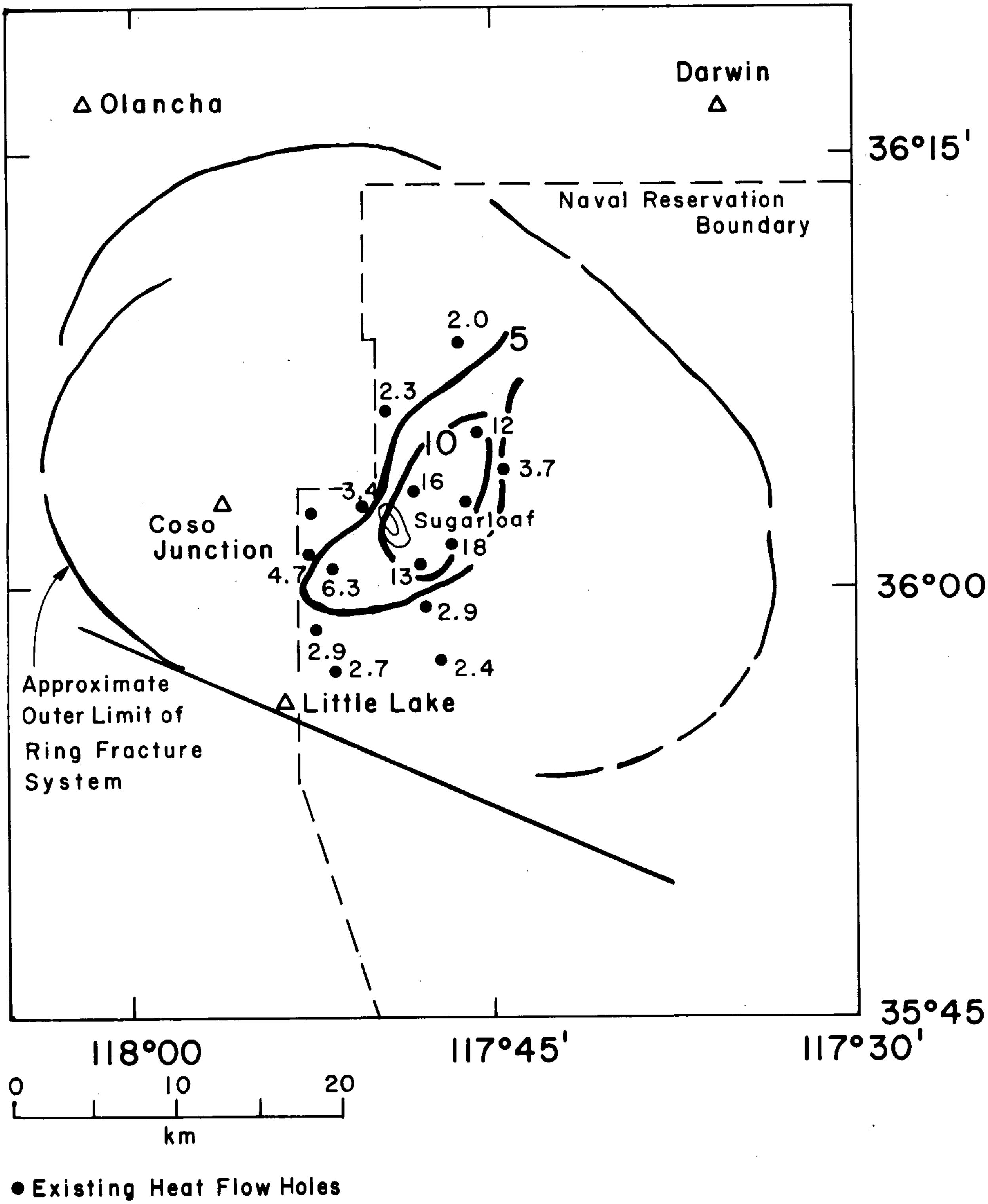

Figure 3.3.2 Map of shallow borehole locations and preliminary heat flow values in HFU (Combs, 1975). The large oval-shaped feature denotes the approximate outer limit of the Coso ring structure system as determined by Duffield (1975).

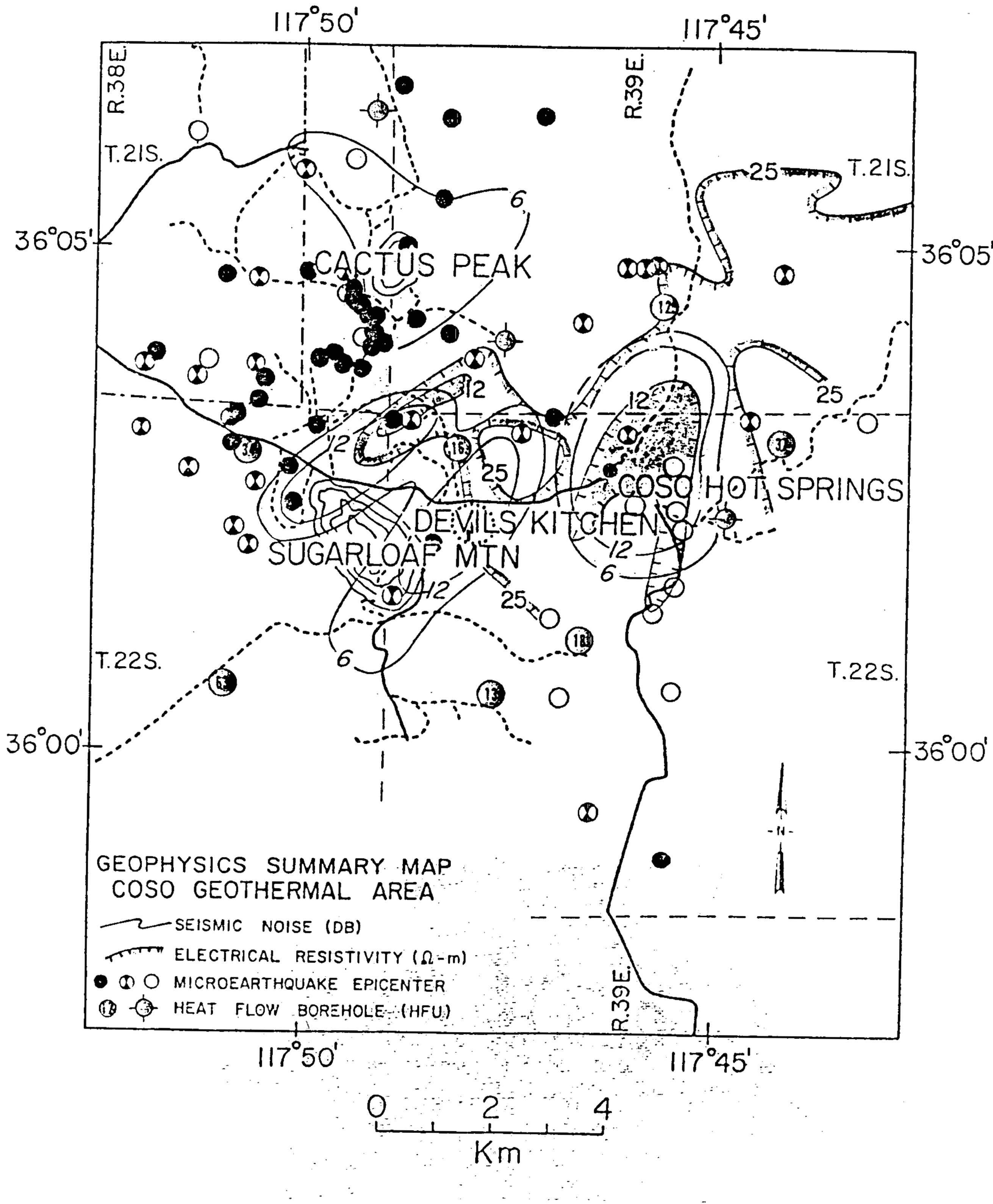

Figure 3.3.3 Geophysics summary map of the Coso Area, located in the center of the Coso ring structure.

1973), and microearthquake epicenters (Combs and Rotstein, 1976) are concentrated in the dome field area.

Predrilling Geological Models. Figure 3.3.4 is an East-West cross section through the Coso geothermal system that summarizes the current consensus of interpretations of existing geological and geophysical data. The heat source for the system is believed to be a silicic-magma chamber, possibly still partially molten, the top of which may lie at a depth of about 5 to 8 km below the surface. HDR resources may exist in several different parts of this system, but initial interest is focused in the dome field area.

Recent mapping by Duffield (1975) in the dome field has shown that the basement rocks near Sugarloaf Mountain and generally throughout the south and central parts of the silicic volcanic dome field are thoroughly shattered, with

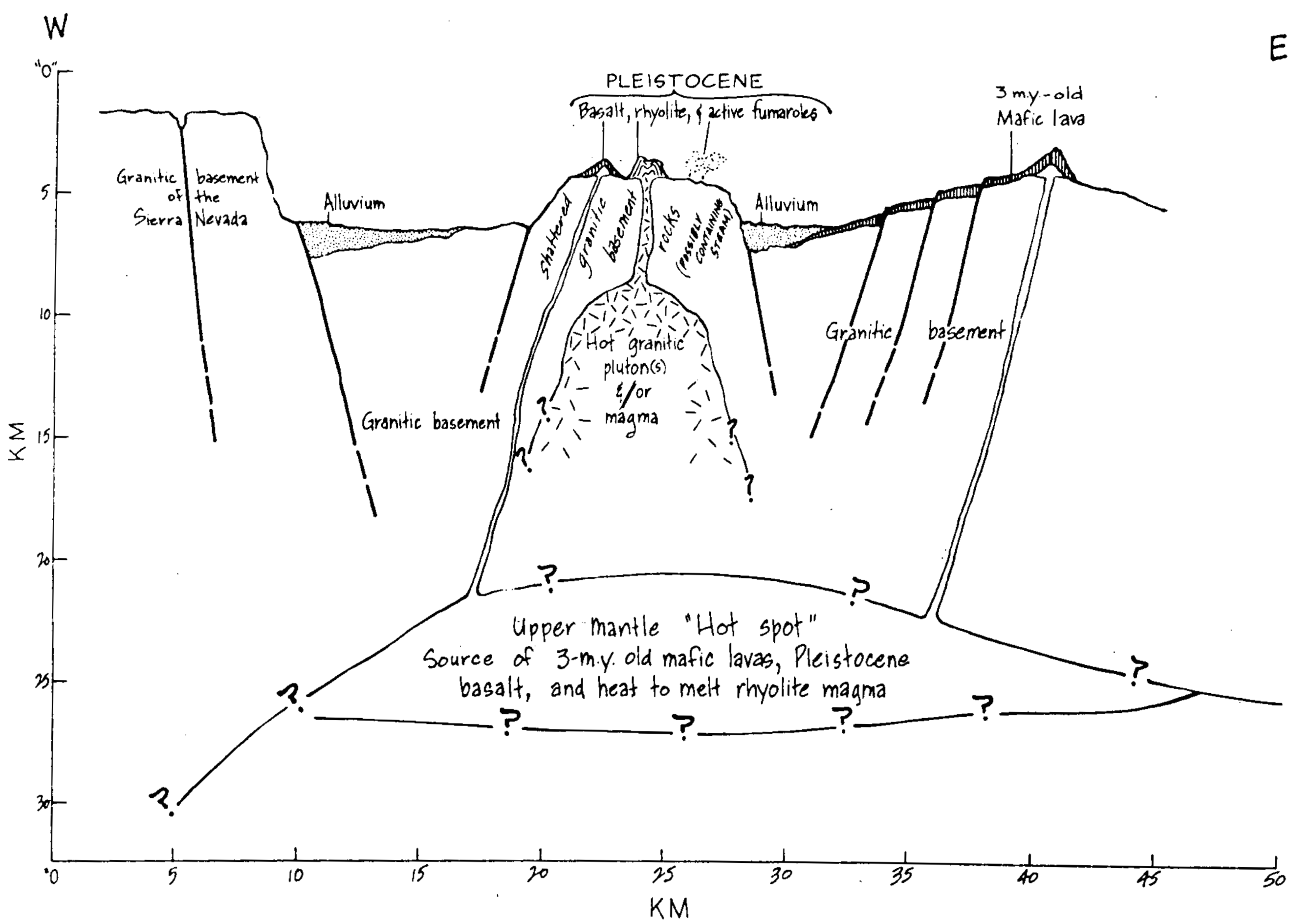

Figure 3.3.4 Predrilling conceptual geological model of the Coso geothermal system.

large areas broken into blocks a metre or less in diameter. There is no reason to believe that this shattering does not extend to significant depth so that a borehole in the central region of the Coso dome field most likely will penetrate shattered, permeable rock to depths of 1 km or more. The high thermal gradient and low Poisson's ratio (Combs, 1975) suggest that it is also likely that steam will be encountered at shallow depth. A major fumarolic area, Devils Kitchen, lies about 1.5 km east of Sugarloaf Mountain. In addition, a heat flow borehole north of Sugarloaf Mountain used by Combs (1975) had to be abandoned when steam was encountered at about 20 m.

The thickness of a possible zone of steam is difficult to predict, but some preliminary results from the study of local earthquakes (Fig. 3.3.3) suggest a possible hot and dry or hot and vapor-dominated zone to several kilometres depth (Combs, 1975; Combs and Rotstein, 1976). Briefly, an anomalously low Poisson's ratio for the granitic basement rocks beneath the rhyolite dome field was observed. This anomaly may result from the presence of steam in fractures in the basement rocks (Combs, 1975; Combs and Rotstein, 1976). However, because the low Poisson's ratio indicates unusually compressible rock, the anomaly might also be caused by large porosity resulting from the probable extreme shattering of these rocks as indicated by the geologic mapping of Duffield (1975). Such shattering and the presence of steam together might cause the observed anomaly.

What rocks will be penetrated by intermediate depth to deep boreholes within the ring structure at Coso will only be known by drilling, followed by a careful examination of the petrology and physical properties of the recovered cuttings and core. It is known, however, that the late Cenozoic rocks at Coso form only a thin veneer over a Mesozoic crystalline basement that is composed principally of granitic plutons and lesser amounts of metamorphic rock.

Intermediate-depth (1500 m) slim boreholes will provide a partial test of the current models for the Coso geothermal system by penetrating the top of what the surface geological and geophysical studies suggest may be a several-kilometer-thick permeable zone of hot, crystalline rocks, with or without steam-filled voids.

Heat flow holes drilled initially were restricted to the obvious thermal anomaly of the rhyolite dome field. However, to delineate more accurately the thermal regime of the Coso ring structure system as defined by Duffield (1975) and to characterize the potential HDR geothermal resources of the Coso geothermal system, 8 to 12 additional shallow heat flow boreholes are being drilled. These additional holes are distributed throughout the ring structure and the surrounding terrain. Current results of the exploration and characterization of the Coso geothermal system are summarized in Table 3.4.I.

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3.4 Summary and Discussion

The various stages of exploration and HDR assessment for three areas so far drilled for HDR purposes are summarized in Table 3.4.I. One principal conclusion is that the Fenton Hill and Marysville sites were not selected for purposes of HDR resource or resource base assessment. The relationship of these projects to the general resource base evaluation problem are (1) in clarifying the nature of the geological and tectonic setting of similar geothermal systems, and (2) in providing guidance in planning future HDR exploration and resource assessment projects.

The Coso project is distinct because the effort is still in the early stages with no deep well drilling yet accomplished. The planning of the slim hole drilling phase is directed toward the broader objectives of demonstrating the utility of that technology in evaluating the HDR potential of the Coso geothermal system. Detailed geophysical and heat flow surveys have thus far largely concentrated on a rather restricted area about 12 by 20 km, roughly centered within the larger (approximately 40-km-diameter) Coso ring structure. Within this small central area shallow HDR may occur in the crystalline rock associated with the young volcanoes and evident hydrothermal activity. By analogy with the Valles Caldera there may be shallow blocks of HDR within the ring fracture or possibly outside it; the latter question has not yet been seriously addressed at Coso.

The HDR site at Fenton Hill, NM, was selected because of its suitability for demonstration of a specific possible HDR-extraction technique. The data used to locate the drill site were largely pre-existing regional studies and some very detailed work focused on the Valles Caldera. The drilling at Fenton Hill has demonstrated that indeed HDR does exist on flanks of the caldera. Although additional studies of the Jemez Plateau in the local region and to the west have been performed, no program currently exists to investigate the extent nor to quantitatively characterize the Valles Caldera geothermal system. Clearly, likely sites for HDR, both at Coso and the Valles Caldera, are the crystalline rocks near or outside the ring fracture systems, at depth where heat is transferred from the magma chamber into low-permeability crystalline rocks.

The Marysville exploration project was developed around a thermal anomaly discovered in the process of a broad regional heat flow study. There were no local surface hydrothermal indications present, and the geologic and tectonic setting were very different from those at the Valles Caldera and the Coso Area. The data obtained in subsequent surface geophysical surveys, geochemistry studies, and additional heat flow holes attempted to resolve the question of whether the thermal anomaly (about 20 HFU maximum) was due to a "blind" hydrothermal convective system or was derived from a conductive heat flux. These data were not definitive in resolving the question but tended to point to the absence of fluid at depth. Thus it seemed likely that the system was conduction dominated, and if so, a heat source must exist relatively close to the surface and therefore a large quantity of HDR could exist. The question was finally resolved with a deep borehole, which entered a warm water (about 93°C) convection system at a depth of about 0.4 km. In hindsight the Marysville project could have benefited by a phase that had included a sequence of slim hole(s). This would have discovered the hydrothermal resource and allowed for some regional definition of its extent, possibly indicated the nature and location of the heat source (still presumed to be a cooling intrusive), and potentially delineated the HDR in the region.

Finally, the heat sources underlying both Coso and Fenton Hill are known to be young silicic magma chambers. At Fenton Hill excellent agreement between observed temperatures and thermal gradients in GT-2 with calculated values have been obtained for a large magma body, emplaced about one million years ago at a depth of 3 to 4 km below the present surface, and with a radius ($\sim$ 12 km) extending somewhat beyond the present ring fracture system ($\sim$ 8 km). Such an intrusion would be largely, but not completely, crystallized at depth at present. It would account for (1) the observed thermal state of the area, (2) alteration of the primary minerals in the GT-2 cores, resulting from fluids expelled from the crystallizing magma chamber, (3) the abundant small fractures, inferred to result from both mechanical and thermal stresses, and (4) associated low-temperature vein and fracture filling by secondary minerals, the result of late-stage fluids from the magma and possibly forced circulation of groundwater in the crystalline rock near the pluton. If so, these features may be common to much igneous-related HDR; in practical terms this may mean that a halo or annulus of hot, low-permeability rock may develop around young silicic plutons as they cool and solidify, an important implication for HDR energy extraction.

Table 3.4.I Summary of experience in hot dry rock exploration and resource assessment.

STAGE IN EXPLORATION AND ASSESSMENT	FENTON HILL, NEW MEXICO	MARYSVILLE, MONTANA	COSO AREA, CALIFORNIA
INTRODUCTION	•Fenton Hill located on western flank of Valles Caldera ~ 32 km west of Los Alamos. •U.S. Forest Service land - within large burned over area. •Situated in southern Rocky Mountains Physiographic Province.	•Marysville located in west central Montana ~ 30 km NW of Helena. •Bureau of Land Management land - within historic gold mining area. •Situated in Northern Rocky Mountains Physiographic Province.	•Coso located in east central California - 50 km N of Ridgecrest. •U.S. Navy Land - within China Lake Naval Weapons Center. •Situated in Basin and Range Physiographic Province.
HISTORICAL BACKGROUND AND REGION SELECTION RATIONALE	•LASL goal was to locate part of a geothermal system where concept for extraction of geothermal energy from hot dry rock could be tested. •Need for hot (>200°C) impermeable rock with ground cover equal to fracture diameter. •Low seismic activity and no active faults. •Close proximity to LASL due to manpower and funding restrictions.	•Higher than normal heat flow observed in granitic pluton during regional study of NW U.S. •Heat flow data interpreted to indicate molten rock near surface; several granitic plutons in western U.S. may be others like Marysville. •Goal to extract geothermal energy from shallow hot rock.	•Obvious surface manifestations of anomalous concentration of geothermal energy. •Several scientific studies made as time and money permitted. •Examination of the hot dry rock geothermal resource potential of the area of young silicic volcanic domes.
REGION SELECTION WITH COMPILATION AND REVIEW OF AVAILABLE DATA	•Very young felsic eruptions 1.4 to <.043 m.y. •Numerous hot springs and high Basin and Range heat flow. •Few large faults with impermeable Precambrian rocks exposed in area. •Depth to basement of 750 m in region of probable high heat flow. •Low seismic energy release.	•Intrusive rocks with ages of 40 and 49 m.y. •Fifteen heat flow determinations between 3 and 20 HFU. •No hot springs in the immediate area although much hydrothermal alteration; several mineral deposits. •Reconnaissance gravity survey. •Regional geological and structural studies.	•Central portion of silicic volcanic domes near fumaroles and active hot springs. •Patterns of snow melt and IR study delineated surface thermal anomalies. •Shallow (<150 m) hot water geothermal wells. •Relatively conductive zones near fumaroles from electrical resistivity. •High seismic ground noise near surface manifestations. •Gravity low interpreted as magmatic intrusion.
NEW DATA ACQUISITION AND TARGETING OF DRILL SITES	•Eleven heat flow holes indicate heat flow of about 5 HFU. •Heat flow increases on west side of Valles Caldera. •Less complex structural setting on west side of caldera. •Drill site targeted on results of heat flow measurements, shallow depth to Precambrian basement, and absence of faults	•Thirteen new heat flow determinations between 2 and 12 HFU. •Detailed geological and structural mapping with petrological studies. •Gravity and both airborne and ground magnetics. •Airborne infrared sensing. •Electrical resistivity and electromagnetic investigations. •Microearthquake and seismic ground noise surveys. •Drill site targeted primarily on heat flow data.	•Geological mapping with geochemistry and geochronology of late Cenozoic (0.04 to 0.96 m.y.) volcanic rocks. •Further gravity and magnetics. •Seven heat flow determinations of 4 to 18 HFU. •Local seismicity and P-wave delays. •Leveling and trilateration surveys. •Drill sites targeted on basis of heat flow results integrated with available geology and geophysics.
PREDRILLING GEOLOGICAL MODELS	•West side of the Valles Caldera on the Jemez Plateau reasonable structural setting in an area of high heat flow where temperature of at least 200°C would be encountered at depths less than 3 km in impermeable Precambrian rock.	•Origin of high heat flow is a buried magma chamber with present molten rock at depths of less than 2 km. •Upward circulation of small amount of hot fluid emplaced as a shallow hot water hydrothermal system in the fractured region above the magma chamber.	•High heat flow and anomalously low Poisson's ratio from seismic studies interpreted as a possible hot and dry or vapor-dominated zone to several kilometers depth. •Low Poisson's ratio caused by large porosity resulting from extreme shattering of rocks.
SLIM HOLE DRILLING AND CONFIRMATION OF AREA FOR HDR	•Heat flow of 3.7 to 4.0 in Precambrian basement rocks. •*In situ* permeability of 5 X 10^{-8} darcys. •Sealed fractures in Precambrian rocks but no active faults within 1.5 km of site. •Fenton Hill area lies in seismically quiet zone. •642 m to Precambrian basement with temperature of 100.4°C at 785 m in GT-1	PHASE NOT INCLUDED IN THE PROJECT	IN PROGRESS •Principal focus of interest is in central area near volcanic domes. •HDR resources may exist outside this area, near or outside the ring fracture.
REFINED GEOLOGICAL MODELS	•Heat source provided by pluton or magma chamber beneath Valles Caldera with heat source perturbing an already high geothermal gradient. •Large block that is free of any faults with surface expression within the areal site. •Basement encountered at about 640 m in GT-1 with sealed fractures and low-permeability Precambrian rocks.	PHASE NOT INCLUDED IN THE PROJECT	FUTURE
DEEP DRILLING, DATA ANALYSIS AND MODEL EVALUATION	•Maximum temperature of 197°C at 2.93 km in GT-2; 205.5°C at 3.06 km in EE-1. •Thermal perturbation of K-Ar and fission track systems. •Permeability from lab measurements and *in situ* range from 10^{-3} to 10^{-8} darcys. •Sealed fractures and microfractures in cores with long sections of hole unfractured. •Electrical resistivity high at site. •Temperatures of ~200°C can be reached in impermeable rocks at depths less than 3 km.	•Maximum temperature 93°C at ~ 0.4 km which was essentially isothermal to 2.07 km. •Water encountered at 465 m with major zones at 583 and 1032 m. •Water flow rates in excess of 16 ℓ/sec were encountered with both upward and downward flow in the borehole. •Shallow molten rock magma chamber model has been eliminated, low temperature hot water geothermal system found. Nature and extent of heat source not yet defined.	FUTURE

4. TECHNIQUES AND RATIONALE FOR HDR ASSESSMENT

This section reviews the current status of knowledge regarding techniques used in HDR assessment and deals briefly with probable future developments in rationale and methods. The principal point to be made is that no specific nor unique techniques exist for HDR resource base assessment, nor has an exploration rationale been developed. At present well-known and obvious geological features are used, such as hot springs or copious young volcanism, to identify the existence of a geothermal system. Possible HDR areas are then defined by identifying the hydrothermal resource and subtracting it from the total. Currently, the most effective exploration tools are volcanic geology (volume, age, and composition of volcanic rocks that reflect the heat source associated with certain geothermal systems), heat flow measurements made in shallow holes, followed by electrical and seismic methods. Knowledge of the relative effectiveness of various exploration methods, applied specifically to HDR resource assessment, is very incomplete. At present reliable data are obtained only by drilling. The most pressing need is for extensive exploration, including drilling, of six to eight representative HDR sites at which all available methods would be used. This experience will provide an empirical basis for evaluating the effectiveness of methods. Even with this, however, the deep parts of (at least several) geothermal systems should be explored by deep drilling.

4.1 Summary of Knowledge

Large volumes of rock at high temperatures are known to exist below all major geothermal areas (Eaton et al., 1975; Healy, 1976; Muffler, 1976) and much of the western United States, as well (Diment et al., 1975). Almost any type of rock, igneous, metamorphic, or sedimentary, may be involved. Although there can be little doubt that some types of recent igneous intrusions in the shallow crust and the associated cooling magmas constitute the ultimate heat sources for all the higher temperature geothermal systems, little is known about the form of the intrusions. When the permeability of a portion of the geothermal system is sufficient, due generally to fractures or pores, meteoric water can circulate downward through the hot rock, extract and convect some heat content of the rocks, and return to the surface through springs or boreholes as thermal water or natural steam (White, 1968, 1973). When that portion of the geothermal system produces economic flow of fluid, it is termed a hydrothermal resource. In addition, geological and geophysical observations at many localities (Smith and Shaw, 1975) indicate that there are particular localized thermal anomalies at shallow depths in the crust of the earth in which the heat is not available from in situ fluid convection systems. In addition, much of the western U.S. is underlain by rocks at substantial temperatures (T > 150°C) at moderate depths (d < 5 km). (See Section 5.7.) These non-molten portions of geothermal systems may be sources of HDR geothermal energy even though they will not produce an economical volume of natural water or steam.

The most fundamental point to be emphasized is that neither specific techniques nor an explicit exploration rationale exists for HDR. The present status of HDR resource exploration consists of a two-stage process in which the existence of a geothermal system is established, then the hydrothermal resource base is delineated -- the remainder may be considered to be potential HDR resources. This important concept is emphasized schematically in Fig. 4.1.1.

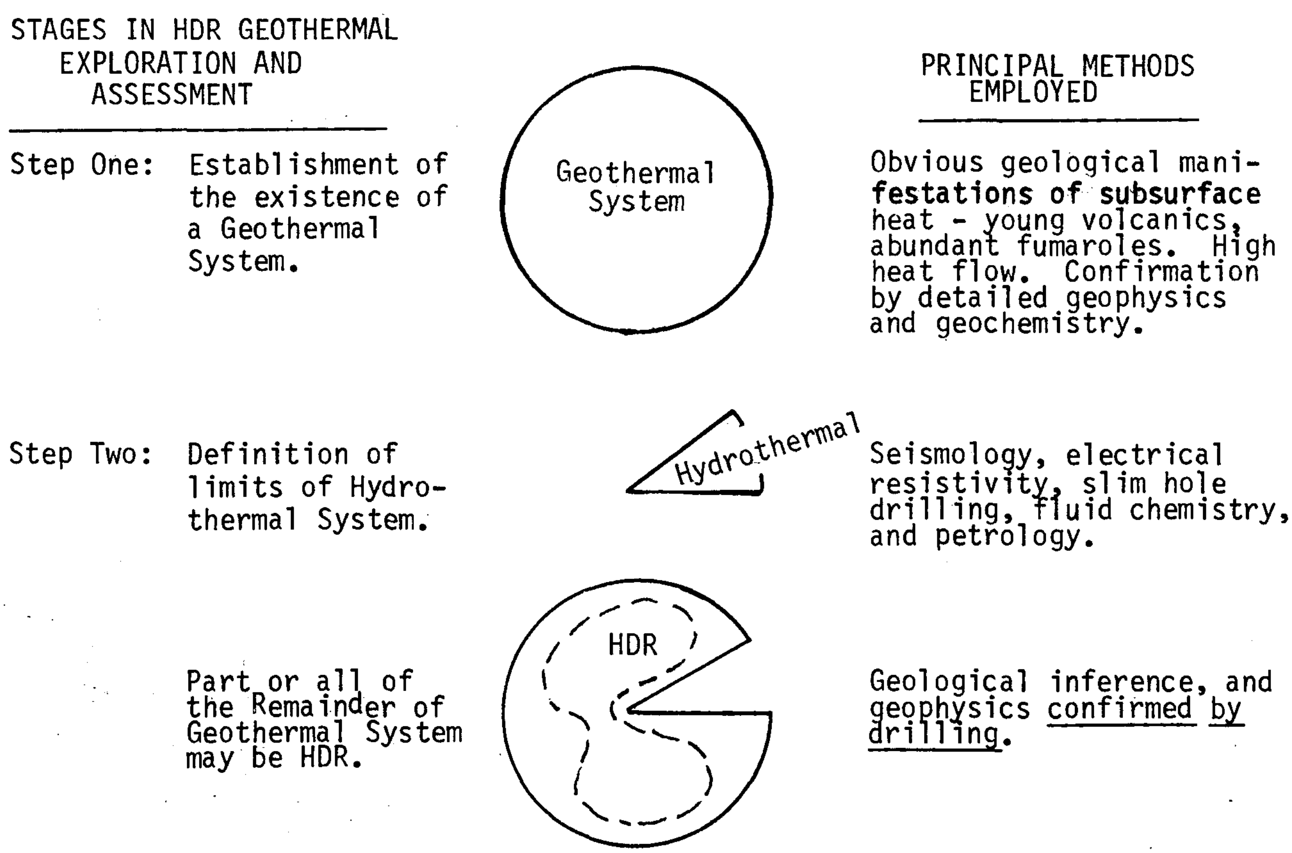

Figure 4.1.1 Diagram of principal techniques utilized to date in HDR assessment.

The role of geology and geophysics in the exploration for geothermal resources has been reviewed in several recent papers (Bodvarsson, 1970; Banwell, 1970, 1973; Combs and Muffler, 1973; Combs, 1976). The emphasis to date, however, has been placed upon discovery exploration and development of hydrothermal resources within geothermal systems. At this stage of development the techniques available for exploring for HDR perhaps are one step more primitive from those used to assess hydrothermal resources.

Geothermal systems commonly contain abrupt, distinctive, and fairly easily measured anomalies -- that is, discontinuities or rather abrupt gradient changes in surface measurements that reflect changes in the physical properties within the subsurface. Because of the mathematical non-uniqueness of the inversion of geophysical data, correlated anomalies from several techniques are sought. In other words, conclusions are drawn by statistical inference using superposition of a body of inadequate information; i.e., no single technique provides sufficient or unique data. Examples of such correlated anomalies occurring within regions of high subsurface temperature are low electrical resistivity, attenuation of high-frequency elastic waves, and changes in ratio of the speed of longitudinal and transverse seismic waves. Clearly the ease with which these anomalies can be detected depends on the degree of contrast in the physical properties of the rocks comprising the geothermal system, and the contrasts between these rocks and those of its surrounding subsurface. Currently, an accurate and unambiguous interpretation of geophysical data is possible only where the subsurface structure is relatively simple and known from drill hole data, and even then it is not always possible. Some drilling is always necessary before a geophysical survey can be properly interpreted because cores and <u>in situ</u> measurements provide the only unambiguous data regarding subsurface materials, physical properties, and structures. The effectiveness of particular geophysical techniques and interpretation of the resulting data may vary greatly from site to site, however. Consequently a technique yielding useful results in a given circumstance may fail in another location because of geological variation between localities.

Geothermal systems usually have irregular shapes and occur in rocks of complex structure and varying type. The current emphasis in geological and geophysical exploration is therefore upon detection of the geothermal systems, that is, unambiguous demonstration of its existence, which also generally implies verification of some model for the heat source, however qualitative that may be. Furthermore, the exploration also seeks to establish bounds on subsurface physical properties, rather than on precise quantitative interpretations. Nevertheless, some indication of the quality, size, and depth of a geothermal system is often obtained. In summary, geological studies and geophysical surveys are conducted with several purposes in mind, namely, to provide data for the location of geothermal systems, to assess the nature of different portions of the system, and to estimate locations for exploratory drill holes.

The occurrence of geothermal systems, the process of differentiation of their interiors into potential resource types, and the subsequent development of geothermal reservoirs, is largely a consequence of deep-seated tectonic processes and physical conditions, and is less determined by the near-surface geological environment. Furthermore, it must be recognized that the fraction of the total surface area of the earth thus far explored in detail is very small; and in fact, only a small percentage of the potentially important geothermal systems have been investigated even in reconnaissance fashion. The selection of regional exploration sites has been strongly biased toward areas with obvious surface thermal manifestations, i.e., near hot springs, geysers, fumaroles, and pools of boiling mud, but many more geothermal systems may exist, especially HDR systems. Surface manifestations may or may not reflect conditions at depth depending on the extent to which the thermal system is masked by overlying non-thermal groundwater horizons. Although there have been several systematic evaluations of geophysical techniques as they relate to discovery of the hydrothermal parts of geothermal systems, little attention has yet been directed to the evaluation of techniques for distinguishing the HDR portions.

Moreover, the presence of surface thermal manifestations generally implies that a geothermal system has been breached by fault movement or erosion, and its contents are being dissipated by natural leakage. Large outflow over an extended period of time will tend to deplete the heat contained in the hydrothermal portions of the system; however, the associated HDR may remain intact after loss or cooling of the convecting fluid from the hydrothermal portions.

Geothermal exploration now should move beyond the stage of geothermal system detection and hydrothermal assessment and must turn toward the search for deep-seated and well-sealed geothermal reservoirs that are unmarked by obvious surface evidence. New geothermal systems are being identified by a process of geological analogy supported by geophysical measurements (see Section 5). However, the exploration strategy for geothermal assessment is still ambiguous and only loosely defined for several reasons, including the variability of the geological environment, a lack of fundamental understanding of the geothermal systems, the lack of realistic geological models to be tested by geophysical surveys, disagreement over interpretation of results from a particular geophysical survey, and, finally (and certainly most important), lack of a broad exploration experience base. To date, neither regional nor local HDR exploration efforts have been specifically focused on potential resource characterization and assessment, although the Coso project now has this as one of its primary goals. A clear need exists to identify the principal types of HDR and their geological settings, and to systematically explore at least one example of each. Only in this way will the empirical background be established for subsequent HDR exploration.

We might expect the evolution of exploration technqiues in HDR to parallel in some respects the experience in the oil and gas industry. During the early development of petroleum exploration, virtually all existing geophysical surveying techniques were used, however, experience demonstrated that only certain ones provide the critical necessary information for detecting petroleum reservoirs. As our HDR geothermal energy experience grows, a similar selection process is occurring. In the past, this lack of an empirical working base has resulted in considerable confusion over the purpose and relative value of a given geophysical surveying technique. Surveys of both conventional and innovative types, often made at considerable expense, have produced data and maps that now appear to have little bearing on the central problem of finding and delineating geothermal systems. Refinements in the geological models of specific well-studied geothermal systems, (e.g., at Long Valley, CA) will be very useful in evaluating the effectiveness of various geophysical techniques, for calibrating the response of geophysical instrumentation in a situation where both structure and the distribution of physical properties are rather well known. Non-relevant anomalies in the geophysical measurement patterns interfere with the construction of significant residual anomaly maps. Such maps are the basic tool conventionally used to distinguish those portions of a system that might contain HDR.

More specifically, to interpret patterns in geophysical measurements, in general, it is essential to cast the geological models and the implied subsurface distribution of geological formations in terms of the three-dimensional distribution of physical properties, such as thermal conductivity, electrical conductivity, seismic velocity, density, magnetic susceptibility, porosity, and/or permeability. This requires laboratory measurements on rock samples and in some cases *in situ* measurements in drill holes. In the absence of such data, estimates are made based on published results on similar geological materials. Experience has shown that laboratory measurements and properties determined *in situ* on the same rocks commonly disagree. This is true for two basic reasons: first, complex natural conditions cannot be simulated easily in the laboratory, and second, the process of sampling (drilling) invariably disturbs rock samples. It is now known that many important physical properties are very sensitive to minor structures, such as microfractures, either natural or induced. Hence, laboratory measurements must be made under variable and closely controlled conditions of temperature, pressure, stress, and pore fluid in order to be relevant to the interpretation of geophysical data at a given site. This is not a triviality from either an experimental or geophysical viewpoint. Finally, where a geophysical survey is undertaken, it is very important to define clearly its purpose and its likely cost effectiveness in terms of probable contribution to the definition of the existence of the geothermal system and the impact the survey may have on the geological model of the system.

4.2 Methods

The known geothermal fields of the world are all associated with some form of volcanic activity, with faulting, with graben formation, with tilting, uplift, or subsidence of crustal blocks. All of these are the result of processes below the earth's crust, in the upper mantle (Healy, 1976; Muffler, 1976). The close spatial and genetic relationship of many geothermal systems to young volcanic centers has formed the basis for a new rationale in the search for geothermal resources. This approach, developed by Smith and Shaw (1975), is to identify large, young, silicic volcanic centers that may be molten or have hot intrusive rocks at depth, that can function as a heat source for the overlying or adjacent HDR geothermal systems and/or hydrothermal convective systems of meteoric water.

Thus, regions selected for preliminary reconnaissance are being found by a process of geological analogy. To assess the resource base of these geological environments, it is necessary to complete a program of detailed geological and structural mapping accompanied by an extensive program of age dating of the local volcanism. Geochemical investigations pertaining to geothermal systems include geochronology, chemical petrology and mineralogy, as well as chemistry of geothermal fluids, which depends on surface thermal manifestations, e.g., hot springs. In general, the geochemical investigations provide an indirect but valuable means of assessing the composition and, to some extent, the volume and physical conditions of the deep interior of the geothermal system's heat source, e.g., the magma chamber. Because surface manifestations, such as hot springs, are not necessarily part of HDR geothermal environments, geochemical studies of underground fluids in the final exploration phase may or may not be valuable in resource assessment, although they certainly will aid in identifying those portions of the system that contain hydrothermal resources, and in general will be crucial for geothermal technology.

Hydrothermal geothermal systems and their immediate surroundings have certain specific physical characteristics, because of their high temperature, that, can generally be detected and mapped by geophysical methods. The temperature within the geothermal system, i.e., the base temperature (Bodvarsson, 1964, 1970), is the most important physical characteristic of a geothermal system. Simply stated, the base temperature is the highest temperature observed in the thermally uniform part of a convecting hydrothermal geothermal system. The physical and chemical processes within these geothermal systems depend critically on this quantity, and the technique of heat extraction has to be selected with regard to these temperature conditions (in combination with other parameters, primarily permeability). Additional important characteristics that can be determined to some extent by geophysical exploration are the probable dimensions of the system, its depth, and the physical conditions prevailing within it. Because the base temperature constitutes the most important physical characteristic of a hydrothermal geothermal system, thermal exploration methods such as geothermal gradient measurements in boreholes and heat flow determinations are of primary importance because they yield data bearing directly on the base temperature. Although no single base temperature may exist in most HDR systems, the importance of direct thermal measurements in boreholes certainly is as fundamental. (In igneous-related HDR systems in which the heat source is a crystallizing magma body, an analogy to the base temperature in hydrothermal systems indeed may exist, namely, the solidus temperature of the magma.) Aside from estimates based on the volume of volcanic rocks or the area of volcanic collapse features, thermal exploration techniques probably provide the most direct method for making a first estimate of the size and potential of a geothermal system. Other geophysical and geochemical methods can provide an indirect determination of the temperatures within a given geothermal system, however, and they may provide an estimate of depth, lateral extent, permeability, water supply, and cap rock distribution, parameters which cannot be obtained using thermal techniques alone.

The application of any geophysical method to exploration for potential geothermal resources is based on the fact that a physical property of the rock is affected in some quantitative, measurable manner by an increase in temperature (Birch and Clark, 1940; Birch, 1943; Hochstein and Hunt, 1970; Keller, 1970; Murase and McBirney, 1973; Spencer and Nur, 1976). Clearly the most reliable indicator of abnormally high subsurface temperatures is the direct determination of an unusually high heat flow. All other geophysical indicators are indirect and depend on the variation of other physical properties as functions of temperature. For example, the application of electrical and electromagnetic methods in geothermal exploration is based on the fact that the electrical conductivity of rocks increases rapidly with increasing temperature. However, it also increases within wet, porous specimens of an otherwise similar rock. The presence of electrolites, such as salt, also increases electrical conductivity. Hence, observed variations in subsurface electrical conductivity may be due to changes in salinity, porosity, pore filling, water content, or composition, rather than temperature alone (Keller, 1970). Under favorable conditions an electrical resistivity survey can provide penetration to depths of 1 km or more; however, because this physical property is a function of many variables, not of temperature alone, the results cannot be uniquely interpreted in terms of a temperature distribution in the subsurface. Nonetheless, electrical resistivity studies have provided some of the most useful data for detecting and mapping geothermal systems, for subsurface geological and structural interpretation, and for monitoring groundwater flow patterns.

During the last few years, a serious effort has been made to test various electromagnetic methods that are designed to monitor the naturally occurring electric and magnetic fields observed at the surface of the earth. The development and testing of the telluric and magnetotelluric methods in geothermal exploration have been motivated partly in an attempt to find a rapid and low-cost method for reconnaissance surveys of relatively large areas and partly in an attempt to increase the depth of penetration under the conditions of high near-surface electrical conductivities that often occur in geothermal areas. We believe these techniques hold much promise.

It has been known for some time that high-temperature hydrothermal areas are characterized by a relatively high level of microearthquake activity (Ward, 1972). The study of these microearthquakes and their precise hypocentral locations provide the data necessary to define the location of active fault zones within a geothermal system, which may be functioning as subsurface conduits for geothermal fluids. In addition, the results of a microearthquake survey can be used to speculate on the subsurface physical characteristics of the geothermal system (Combs and Rotstein, 1976). On the other hand, Olsen et al. (1976) report that the Valles Caldera area is very quiet seismically, relative to its surroundings. Iyer and Hitchcock (1976) observed a high microseismic noise level in Long Valley, but interestingly under the eastern half, whereas the HDR resources are inferred to be concentrated in the west (see Section 5.5A.). At present, the relationship between microseismic noise and HDR resources is not known.

Other geophysical measurement techniques have been used in geothermal exploration or have been recommended. These include survey methods such as gravity, magnetic, active seismic, airborne infrared, microwave radiometry, and satellite imagery. These techniques will not be discussed in detail because none of them are unique in their ability to define the existence of a geothermal system.

The various geological, geochemical, and geophysical exploration methods that will be valuable in performing HDR resource assessment are summarized in Table 4.I. Each method is summarized with respect to the data observed, the physical properties sought, the usual interpretation and relative utility, as well as the problems and possible ambiguities associated with each technique. It is important to recognize that two stages of exploration are represented

Table 4.I Summary of exploration for potential use in HDR resource assessment.

ACTIVITY & LOCALE	TECHNIQUE	DATA AND/OR OBSERVATION	GEOTHERMAL SYSTEM IDENTIFICATION: PROPERTIES SOUGHT	GEOTHERMAL SYSTEM IDENTIFICATION: INTERPRETATION	GEOTHERMAL SYSTEM IDENTIFICATION: PROBLEMS, AMBIGUITIES, REMARKS	VALLES CALDERA	MARYSVILLE THERMAL ANOMALY	COSO RING STRUCTURE	HOT DRY ROCK RESOURCE ASSESSMENT: PROPERTIES SOUGHT	HOT DRY ROCK RESOURCE ASSESSMENT: INTREPRETATION	HOT DRY ROCK RESOURCE ASSESSMENT: PROBLEMS AMBIGUITIES REMARKS	FENTON HILL	MARYSVILLE	COSO
GEOLOGY AND GEOCHEMISTRY — Regional	Mapping, Petrology & Geochemistry	Volcanism, Age, Type	Young, silicic rocks preferred, shallow source	Shallow magma chamber with residual heat	Depth commonly uncertain	1.1-1.4 m.y. Bandelier Tuff, rhyolitic	None	Rhyolite domes as young as 0.04 m.y.	Low-permeability reservoir			Pre-Є granitic reservoir		Young
	Mapping Structure	Faults	Highly faulted for hydrothermal, unfaulted for HDR	Evaluation of permeability		Highly faulted caldera interior, few faults outside	Several NW striking faults	Highly faulted caldera interior	Absence of faults, especially active	Low permeability, minimal induced seismic risk		Site within large coherent unfaulted block		
Local	Geochemistry	Absence or presence of hot springs, temp., chem.	Hot water, high Si and high alkali content	High-temperature heat source at depth		Hot spring in & around caldera	None	Abundant Hot springs & fumaroles						
GEOPHYSICS — Regional	Seismic, Passive: Teleseisms	Vp, Vs, G, Q	Vp, Vs delays; low ∂ and low Q	Existence of magma chamber at depth					Vp, Vs delays, low Q	Low-velocity layer caused by partial melt, or thin crust		Thin crust		Thin Crust
	Seismic, Passive: Local Seisms	Vp, Vs, G, Q				Low	Aseismic	Active	Low number of events	Little reopening of fractures and hence low permeability. Little seismic risk.		Low activity	Seismic belt	Seismic belt. High risk.
	Seismic: Noise	Number & frequency peak				Data not available	Low noise within heat flow anom.	High noise	Low noise level			Low		High
	Aeromagnetic	Strength of local magnetic field	Magnetic low	Shallow Curie point temperature indicating hot rock at shallow depth	Low spatial resolution, multiple causes of mag. lows	High			Lows or highs useful, depending on local geology			High		
	Gravity	Strength of local gravity field	Gravity low	Existence of possible magma chamber of depth and its shape	Commonly small Δρ so no resolution; low spatial resolution	Low under caldera	Low assoc. with heat-flow anom.	Low	Trend of gravity lows	Deep-seated emplacement of silicic rocks		Low along regional trend		
Local	Magneto Telluric (Passive)	Response to perturbations of earth's field				Regional low Ω at depth	High Ω at 2-6 km		Low Ω at great depth	Electrically conductive structure due to thermal enhancement		Straddle regional trend of low Ω at depth		
	Electromagnetic (Active)	Response of natural field to induced field				Low Ω deep			High Ω at shallow depth. Low Ω at great depth.	Dry rock underlain by thermally enhanced rock--absence of hydrothermal system		High Ω shallow. Low Ω deep.	Low Ω shallow. Low Ω deep.	
	Active Seismic	Vp,Vs,O,Q				Used to map top of Pre Є basement			Absence of faults			Occasional fault		
	Electrical Resistivity	Resistivity with depth				Presumed low within caldera	Shallow high Ω	Low Ω near dome field	High resistivity	Absence of hydrothermal system		High Ω shallow	Low Ω shallow	Low Ω shallow
SHALLOW HOLES	Heat Flow	Temp. vs Depth	High thermal gradient	Heat source at depth	Near-surface hydrologic effects	High heat flow along Rio Grande Rift	High heat flow 3.1-19.5 HFU	High heat flow	High linear thermal gradient but heat flow <6 HFU	Heat source at depth; heat transfer by conduction		∿5 at surface ∿3.7 in Pre Є	19 HFU	15-18 HFU
DRILLING	Cores	Mineralogy, petrology geochemistry, physical properties				GT-1 indicated granitic basement	Empire shale over granite porph.	In progress	Sealed fractures. Low-solubility minerals	Low permeability. Low level of dissolved solids in fluids.		Sealed fracture. Low-solubility minerals	Open fractures	
	In Situ: Temp.	Thermal state and conductivity				100°C at 785 m	93-96°C at 2.07 km		High temp.	High-temperature heat source at depth.		200°C at 3 km		
	In Situ: Lithology	Cuttings, logs				Granitic, minor amphibolite						Pre-Є granitic rocks		
	In Situ: Fluid Injection	State of stress and permeability				5×10^{-8} to 6×10^{-3} darcys	Permeable					∿ 1400 psi for hydrofrac		

*The blanks in this table indicate that insufficient data exist for an entry to be made; hence, these also communicate information regarding the status of knowledge for various techniques, namely that our knowledge is quite fragmentary.

here, namely an early stage, which seeks to demonstrate the existence of a geothermal system, and a second, designed to quantitatively characterize it in terms of a model (see Fig. 4.1.1) and especially to delineate potential HDR resources within the system. The summary table, then, intends first to focus on the use of the indicated techniques in a region where a geothermal system has been inferred, and second to describe the use of the techniques to define HDR occurrences within the broader geothermal system. The utility of various techniques used at the three HDR sites presented in Section 3 is summarized in the table. However, it is important to remember that the activities at the Fenton Hill and Marysville sites were not directed primarily at resource base assessments.

The many blanks in Table 4.I perhaps communicate directly the most important message of this section -- namely, that our experience with all the exploration techniques for HDR assessment (geological, geochemical, geophysical) is inadequate. This is because we have yet to apply them in a uniform and systematic way in a suite of very well understood areas carefully selected to represent the major types of possible HDR occurrences. The detailed understanding of this suite of sites necessary to test the exploration methods will require drilling for information; we can state with certainty that one or two very deep drill holes will be required to understand igneous-related HDR systems (see Shoemaker and Swann, 1975). These few well-studied areas will serve as geological calibration sites for HDR exploration methods (while at the same time provide valuable and precise resource base assessments). Only after this is done can available exploration methods be evaluated and utilized in a cost-effective manner.

Finally, there is a lesson to be drawn from exploration experience to date and detailed descriptions of the three case histories in the previous section. The three cases are geothermal systems believed to be the consequence of deeper igneous heat sources. The simple lesson is that the deep structure of these systems cannot be inferred until at least one is explored by deep drilling. Ideally this deep drilling should penetrate the roof into the underlying magma chamber. The most fundamental question in all igneous-related geothermal systems is the depth to the magma chamber. There is abundant geological, petrochemical, and geophysical evidence suggesting that this depth is in the range of 3 to 6 km, but no example has been explored at depth. The scientific rationale for such an ambitious undertaking has been recently developed in detail, (Shoemaker and Swann, 1975) in the context of the proposed U.S. Continental Drilling Program. Data regarding conditions within the deep parts of active geothermal systems cannot be inferred from the study of eroded analogs, valuable as this is in many ways, because such a system is a corpse -- temperatures, fluid content, and the circulation system are different. Similarly, geophysical techniques are limited by the non-uniqueness of each geophysical method and the decrease in resolving power with depth. This means there is no substitute for deep drilling -- for information.

4.3 State of the Art and Future Methods

We stated earlier that at present the exploration rationale for HDR consists of two parts. The first consists of demonstration of the existence of a heat source within a geothermal system; the second, of determination of those parts of the geothermal system that may constitute potential HDR resources by identifying the hydrothermal resources and subtracting them from the total system. It is unlikely that this overall rationale will change.

The identification of igneous-related geothermal systems is in an advanced state of development. In general, magmas and in some regions tectonic activity influencing the crust (such as the coincidence of continental crust with the mid-ocean ridge or rift-system as in Iceland, Ethiopia, and possibly Mexico and California) provide the necessary heat source for presently exploited geothermal systems. However, most, if not all, known high-temperature geothermal areas show a close connection with eruptive centers that have produced silicic lava (Smith and Shaw, 1975). For example, in Iceland the volcanism is predominantly mafic, but the largest high-temperature geothermal areas are located near those volcanic centers that have had recent silicic eruptions (Bodvarsson, 1970). Hence, both experience and inference (Smith and Shaw, 1975) suggest that the highest grade deposits of heat in the crust will be associated with silicic volcanic centers.

These igneous-related HDR geothermal occurrences are identified by determination of the location and size of the deep igneous mass providing the heat. Experience shows that concern must be exercised with several potentially deceptive geothermal situations. One is a buried hydrothermal convection system sealed from the surface by a non-convecting cap of impermeable rock in which heat transfer is conduction dominated. Another is simply a hydrothermal system without obvious manifestations, as can occur in rocks of low but finite permeability -- sufficiently high to permit convective transfer to dominate. In both cases, measured near-surface thermal gradients can appear to be conductive and suggest a buried heat source of significantly higher temperature and larger size than may in fact exist. A major question is the depth to which such gradients can be extrapolated. These situations should be resolvable from the desired case of a truly viable buried igneous heat source, using surface thermal gradient measurements and heat flow determinations provided one or two boreholes penetrate below the surface levels of the system. A particularly pointed example is the deep hydrothermal system at Marysville, which would have been discovered in this way, before the costly drilling of a production-size hole. Experience has demonstrated that temperature measurement in deep boreholes is the only reliable means of providing information on the existence and base temperature of a hidden hydrothermal system. Clearly a critical need exists for relatively low-cost (probably slim hole) drilling that emphasizes obtaining information.

Heat stored in the conduction-dominated (and non-igneous) parts of the crust is an enormous resource base. Exploration techniques for these non-igneous geothermal systems are based upon determination of a broad, high regional conductive heat flow, the heat transfer mode, the nature of the thermal conductivity of the near-surface layers, and knowledge of the depth to the basement crystalline rock. In general, thermal gradient measurements and heat flow determinations in shallow boreholes extending below the level disturbed by local groundwater circulation will suffice to locate regions of interest. Depth to basement can be determined by reflection seismic surveys and verified by other geophysical techniques. Selection of potential energy extraction sites may not be as difficult for this type of HDR as it is for igneous-related sites, because the heat is of lower grade and more diffuse.

The second phase of the HDR assessment requires the use of exploration techniques that can evaluate the geothermal system sufficiently so that the hydrothermal and HDR portions can be differentiated and characterized. A large variety of geophysical methods exist that can, in principle, be used to map the subsurface temperature distribution and determine fluid content. The problem is to select the most suitable method from the point of view of field operations, processing of data, and the interpretation of the results in terms of realistic geological models. We are therefore concerned with the identification and development of geophysical methods to determine the depth and areal extent of large volumes of hot rock within the crust associated with geothermal systems. Because of their considerable depth of penetration and potential for delineating fluid zones, electrical, electromagnetic, and seismic techniques are the types of geophysical surveys that are particularly suited for studying the deep characterics of the system. To date no definitive criteria exist, and a lack of exploration experience precludes the establishment of a rationale for the second phase of the assessment. It is instructive to review experience, however. In the central volcanic region of the North Island of New Zealand, where the Broadlands, Rotokawa, Tauhara, and Waiotapu thermal areas are situated, Keller (1970) located an apparent deep heat source that has been interpreted to be a slab of basalt with a partially molten interior (Banwell, 1970). From an extensive magnetotelluric survey of the neovolcanic zone in Iceland, Hermance et al. (1976) have found systemically lower resistivity than was found in the older crust and have interpreted the lower resistivity to be caused by a small partial melt fraction, i.e., several percent, of basalt in the deep crust. Zablocki (1976) has used the prominent self-potential anomalies found at Kilauea Volcano in Hawaii to determine the position of magma pockets on the flanks of the volcano. Magma chambers and movement of magma within volcanoes have been recognized using seismological techniques, e.g., the seismic prospecting carried out by Hayakawa (1970) at Showa-Shinzan in Japan and by Fedotov et al. (1976) at the Avachinsky Volcano on Kamchatka; the use of seismic body waves from microearthquakes by Matumoto (1971) to identify the magma chamber underlying Mount Katmai Volcano in Alaska; and the use of teleseismic P-delay studies by Steeples and Iyer (1976) to postulate magma chambers at Yellowstone National Park, the Geysers, and Long Valley in the United States. However, in none of these geothermal systems have the HDR portions been identified or their potential established. Ultimately, deep drilling will be required to establish the facts concerning the deep parts of these systems, to establish unequivocally the HDR occurrences, and most importantly to permit calibration of the techniques against known geology.

4.4 Future Selection of Geothermal Regions and Localities

During the next few years, exploration for HDR geothermal occurrences should be focused at the geothermal systems associated with large, young silicic volcanic centers. A list of these, and other possible igneous-related sites, is contained in Section 5. However, exploration should be extended to include geological environments such as the Basin and Range Province. Substantial effort should be expended at selected geothermal systems where extensive geological and geophysical investigations have already been accomplished in order to define clearly the heat source and to differentiate various types of geothermal systems present. Additional areas should be selected by a process of geological analogy to provide data on the major types of occurrence of HDR resources, and also to locate promising geothermal systems.

Within each type of site, the HDR portion will be defined by a process of systematic detailed geological mapping, supported by extensive chemical petrology including age determinations on the local volcanic rocks. The existing geochemical and geophysical data should be augmented by additional surveys and measurements on regional, areal, and local scales. These data will guide the location of sites for heat flow surveys within the region or, on a local scale, for more specific purposes. It is likely that a series of shallow (approximately 100-m-deep) heat flow boreholes must be drilled at each locality where HDR may occur because heat flow determinations provide critical data for the geological model of any geothermal system and also may be the most direct method for making an initial estimate of its size. Thermal exploration techniques in themselves, however, cannot provide a direct estimate of the depth, lateral extent, and permeability of a geothermal system; other geophysical methods must then be utilized after a thermal anomaly has been identified. At this point, preliminary quantitative models for the system can be generated. An intermediate-depth exploratory borehole can then be sited and drilled to test the models.

Because of the effect of high temperatures on the physical parameters measured and depth of penetration, electrical, electromagnetic, and seismic techniques are likely to be the geophysical surveying methods of greatest use in support of heat flow determinations. As many of these techniques as possible should be used to augment the heat flow determinations and to provide information on where a series of intermediate-depth exploratory geothermal boreholes can be planned and sited, as well as to provide experience and calibration of the use of the techniques.

All of the available geological, geochemical, and geophysical data for each possible future site should be processed, analyzed, and interpreted in terms of proposed geological models of the geothermal system. After the drilling phase has been completed, refinements in the geological models can be made and the exploration and evaluation process continued with new hypotheses and models generated that can be examined and ultimately verified with further deep drilling. The site can then be developed or abandoned, on the basis of a sound model.

The principal conclusions of this section, which should impact our future activities in both site selection and development of exploration methods for HDR geothermal energy are:

- A suite of sites, perhaps four to six, should be selected to be representative of the principal types of HDR occurrences, and should be explored in detail, including extensive drilling programs. These will serve as geological calibration sites for evaluating various exploration methods, as well as providing the basis for more precise assessment.
- Drilling will be necessary to acquire reliable data regarding the viability of the deep-seated heat source in all geothermal systems. Therefore, relatively low-cost (slim hole) drilling methods must be developed with an emphasis on information retrieval.
- Knowledge of the deeper parts of igneous-related geothermal systems will require very deep drilling of one or two sites, ideally with penetration into the magma chamber - as described in detail in the proposed U.S. Continental Drilling Program (Shoemaker and Swann, 1975).

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5. POTENTIAL SITES AND PRESENT STATUS OF KNOWLEDGE

5.1 Introduction

Two fundamentally different types of HDR are believed to exist, namely, those associated with igneous intrusions or volcanoes and those in which the heat source is the conducted heat from the earth's interior. Within the conductive parts of the crust large-scale linear features of regional extent, which are believed to be deeply rooted fractures, may concentrate heat as they apparently concentrate volcanism and ore bodies. This latter category of HDR resource site will not be discussed in detail in this report because it is largely uninvestigated, is somewhat speculative in nature, and data are inadequate. The global distribution of heat in the earth's crust, and therefore of HDR resources, is clearly controlled by tectonics -- HDR is concentrated (1) in the volcanic-seismic belts associated with convergent plate margins, such as in western parts of North and South America and (2) on or near the mid-ocean ridge and world rift system as in Iceland and Ethiopia (possibly Baja California), where plates diverge. The ultimate source of heat in the earth's interior is largely radioactive decay of certain long-lived radionuclides (U^{235}, U^{238}, Th^{232}, and K^{40}), although locally chemical reaction heat may be important, as during metamorphism. Locally within the crust unusual concentrations of radioactivity can provide HDR resources. For the practical purposes of HDR assessment, it is convenient to recognize the following two categories of regional HDR sites:

- o <u>Igneous-related sites</u>. Generally associated with young volcanism but intrusive bodies of magma without volcanics probably exist.
- o <u>Conduction-dominated non-igneous areas</u>. Some with high heat flow and some with important internal sources of heat, principally radiogenic heat, although chemical reaction heat may contribute locally.

In the following discussions, the emphasis is on igneous-related sites because these are relatively well understood and also because they constitute the high-grade HDR sites in the crust. In the concluding section of this report, however, the vast amount of heat stored in the second category is emphasized, namely, the deeper portions of the conduction-dominated parts of the continental crust. As drilling and extraction technology evolve, this heat may make an important contribution to national energy needs.

This section of the report begins with a discussion of four potential regions recommended by HDRAP for future HDR assessment. Next, the HDR resource base in the conduction-dominated parts of the crust is described and an estimate is made of that part of the total resource base potentially available for power generation, that is, the part of the resource base exceeding 150°C at depths shallower than 10 km. Appendix A contains brief descriptions of 13 additional regions that may contain HDR, -- most of which are igneous-related sites.

Finally, we point out that the correct approach to the evaluation of the HDR resource is somewhat analogous to that commonly taken for ore deposits. That is, specific deposits must be evaluated in terms of both size and grade. Resources stored in igneous-related sites are likely to be of higher grade (temperature) but of smaller size than those dispersed in the deeper parts of the crust. The former are analogous to high-grade vein deposits of ore minerals, whereas the latter are more similar to large, low-grade "porphyry" deposits. Both face practical problems not common in ore extraction, however. Igneous-related, high-temperature environments, although at shallower depths, face problems of instrument failure and equipment lifetime; the low-rank deposits stored in the conduction-dominated resources dispersed in the crust will require deep drilling and reservoir engineering at depth.

5.2 Igneous-Related HDR Resource Sites, Category 1

Smith and Shaw (1975) have identified about 19 volcanic loci within the conterminous U.S. that may be expected to contain magma or high-temperature solidified magma at temperatures close to or above 650°C. These are listed in Table 5.2.I, along with two sites in Alaska. It is believed that there are significant thermal anomalies associated with these volcanic centers above 10 km depth and that many of these magmatic systems may extend up to the 3- to 5-km-depth range.

Table 5.2.II contains a suggested classification of volcanic and igneous-related HDR sites, which together are referred to as Category 1 sites. Category 1 is further subdivided into types of volcanic systems listed here in approximate descending order of potential as HDR sites. Overlaps in HDR potential among these subdivisions certainly must occur because of variations in age, depth, rock permeability, and other unknown factors. If the first

priority in site selection is to be shallow, low-permeability rocks in the temperature range 200 to 650°C, then such sites are most likely to be in Category 1A, namely silicic volcanic centers. Table 5.2.III lists some Category 1A sites.

Table 5.5.VI, later in this section, contains the status of available pertinent scientific information on each site of Table 5.2.III. Each type of information is rated on a scale of 1 to 3: (1) detailed information available, (2) adequate information to begin slim hole drilling program, and (3) inadequate information.

Table 5.2.I Volcanic loci within the United States expected to contain hot dry rock associated with magmatic heat sources.

ARIZONA

1. San Francisco Peaks*

CALIFORNIA

2. Lassen Peak
3. Clear Lake
4. Long Valley*
5. Salton Sea
6. Coso Mountains**
7. Mono Domes
8. Medicine Lake*
9. Mount Shasta*

WYOMING

10. Island Park - Huckleberry Ridge
11. Yellowstone

IDAHO

12. Blackfoot Domes

NEW MEXICO

13. Valles Caldera**

OREGON

14. Crater Lake
15. Newberry Caldera
16. South Sister

UTAH

17. Mineral Mountains

WASHINGTON

18. Glacier Peak
19. Mt. St. Helens

ALASKA

20. Mt. Edgecumbe
21. Mt. Wrangell

(Approximately 25 other andesitic volcanic centers of the Aleutians and Alaska Peninsula are not listed.)

*Sites recommended by HDRAP for immediate assessment.

**Sites currently being investigated with ERDA support for HDR geothermal energy or demonstration.

Table 5.2.II Subdivisions of volcanic or igneous-related systems - Category 1.

A. Silicic volcanic systems

1. Large calderas
2. Large dome clusters
3. Small calderas
4. Small dome clusters and single domes
5. Andesitic stratovolcanoes with silicic vents
6. Other

B. Basic volcanic systems

1. Calderas of shield volcanoes
2. Andesitic stratovolcanoes
3. Large vent clusters
4. Small vent clusters and single vents
5. Other

Table 5.2.III Examples of Category 1A Sites - silicic centers.

Geothermal System	Subtype (Table 5.2.II)
Long Valley, CA	1A1
*Valles Caldera, NM	1A1
Island Park, ID	1A1
Yellowstone, WY	1A1
*Coso Mountains, CA	1A2
Mineral Mountains, UT	1A2
Mono Craters, CA	1A2
San Francisco Peaks, AZ	1A2 (1B3)
Clear Lake, CA	1A2 1A6
Medicine Lake, CA	1A3
Lassen Peak, CA	1A4, 1A5
Blackfoot Domes, ID	1A4
Mt. Shasta, CA	1A5
Mt. Edgecumbe, AK	1A5

*HDR experiments under way.

Table 5.2.IV Examples of Category 1B Sites - basic volcanic centers.

Geothermal System	Subtype
Kilauea Caldera, HA	1B1
Mt. Hood, OR	1B2
Mt. Baker, WA	1B2
San Francisco Peaks, AZ	1B3 (1A2)
Cinder Cone, CA	1B4

The five sites shown in Table 5.2.IV are listed as representative of Category 1B, but it is doubtful that many are currently defensible as suitable HDR sites based upon presently available data. However, characterization of the resource base and the requirement to create geological calibration sites for development of exploration methods will justify drilling experiments in at least some of these areas.

5.3 Category 2

The state of knowledge of Category 2 regional HDR sites indicates that identification and modeling of the resource base for these geothermal systems should be deferred to subsequent HDRAP reports. Section 5.7 contains a brief discussion of the potential HDR resources in Category 2.

5.4 Resource Models for Category 1 Sites

The magnitude of a thermal anomaly associated with intrusive igneous rocks will be directly proportional to the intrusion's volume and inversely related to its age. Figure 5.4.1 modified from Smith and Shaw (1975), is a log-log plot of the estimated volume of the magma chamber against its minimum age, estimated by the age of the youngest associated volcanic rocks. Such plots are commonly called Smith-Shaw diagrams. The straight lines are calculated cooling times as a function of volume for various assumptions regarding magma chamber shape and the importance of convection. On this diagram, geothermal systems falling in the lower-right side of the diagram have the greatest geothermal potential because of their large size, young age, or both. The reader will note that only 14 of the 21 regional sites listed in Table 5.2.I are shown on this figure. These are felt to have more favorable types of basement rock for existence of HDR resources, because basement rocks with relatively low permeability and low water contents are probably most advantageous as HDR resources. In probable order of increasing permeability and groundwater capacity, five general categories of basement rock (see Table 5.4.I) can be defined as follows:

(1) Granitic or other plutonic basement,
(2) Precambrian and Paleozoic metamorphic,
(3) Mesozoic folded metamorphics,
(4) Paleozoic or Mesozoic sediments (with no or moderate deformation),
(5) Cenozoic volcanics or sediments.

Table 5.4.I Relationship of basement rock types and present knowledge of permeability.

	Basement Rock Type	Approximate Probable Permeability Range (darcy)	Remarks
1.	Granitic or other plutonic rocks	10^{-6} to 10^{-8}	10^{-7} measured *in situ* in Fenton Hill drill hole GT-2; 10^{-8} in diabase in Michigan Basin project.
2.	Precambrian and Paleozoic metamorphic rocks	10^{-2} to 10^{-4}	Reasonable average value, 10^{-3} for unfractured rocks; data sparse.
3.	Mesozoic folded metamorphic rocks	10^{-1} to 10^{-3}	Ibid, 10^{-2}
4.	Paleozoic and Mesozoic sediments with little or moderate deformation	10^{-1} to 10^{-3}	Ibid, 10^{-2}
5.	Cenozoic volcanics and sediments	10^{3} to 1 (and some sediments to 10^{-3})	Ibid, 1 to 10

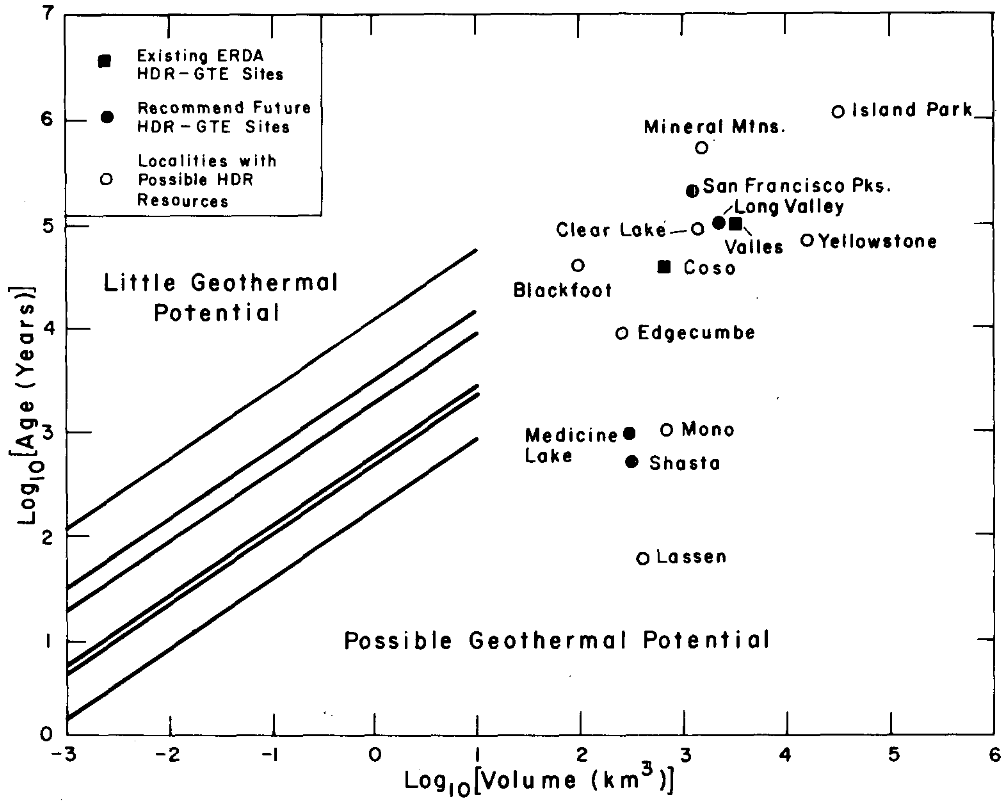

Figure 5.4.1 A (Smith-Shaw) plot of the age of the youngest volcanic rocks as a function of estimated volume of various magma chambers, after Smith and Shaw (1975). The lines indicate calculated cooling times for various assumed models of pluton geometry and heat transfer. Only 14 of the 21 Category 1A HDR sites are shown, namely, those believed to occur in favorable (low-permeability) basement terranes.

Using this classification scheme, those sites with basement categories 4 and 5 were eliminated; the remaining 14 are those plotted on Fig. 5.4.1. In Fig. 5.4.2 each of the 21 volcanic areas listed above are plotted on a diagram showing the quality of the basement rocks against the volume of each magma chamber. Approximate permeabilities of each category of basement rock type is shown in Table 5.4.I.

In general, three types of potential geothermal resources are associated with geothermal systems resulting from igneous heat sources, namely, magma, hydrothermal, and HDR. The partitioning of available heat within these three will vary as the system ages (Muffler, 1976). The heat initially carried into the crust by the magma will be delivered by conduction (and convection near the contacts) to its surroundings creating both HDR and hydrothermal heat whose magnitude varies with time according to the local thermal regime. Typical

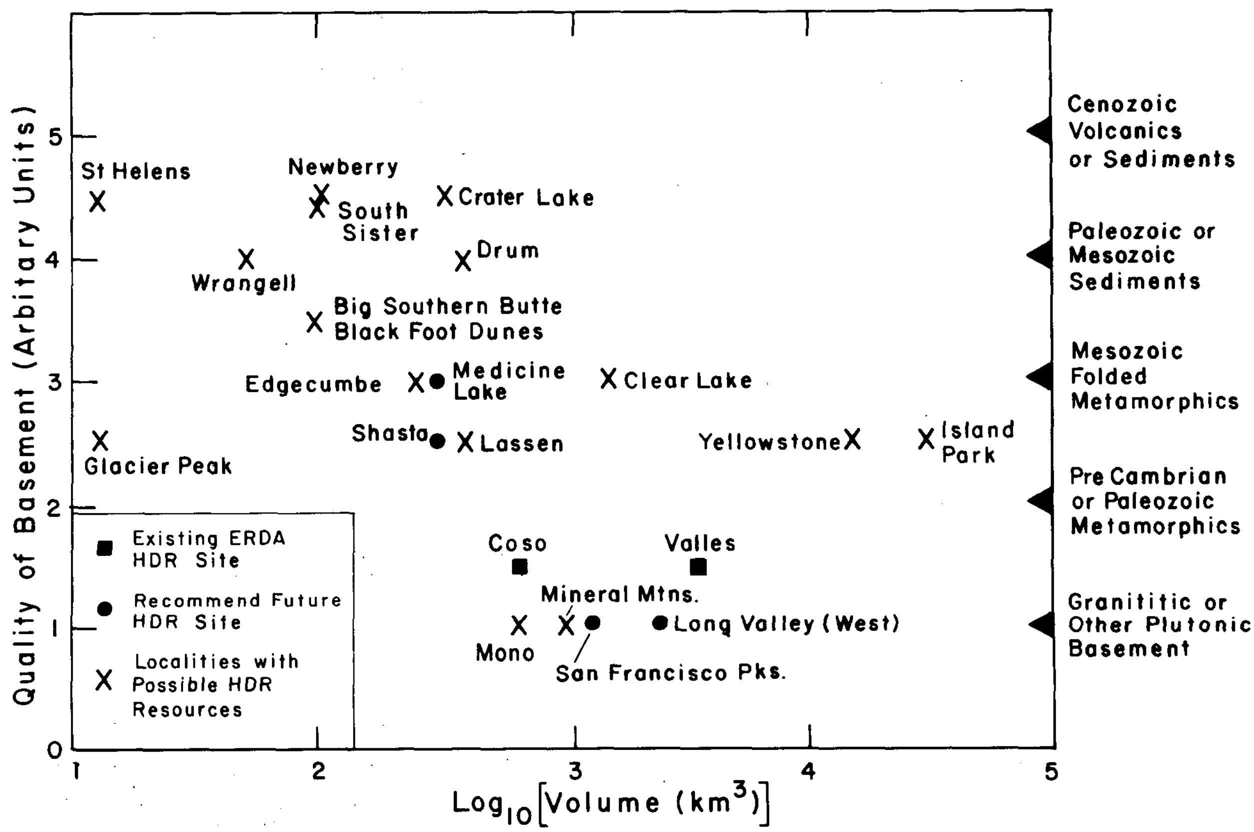

Figure 5.4.2 Estimated basement rock ranking versus volume for Category 1A regional sites.

results (e.g., Lachenbruch et al., 1976; Norton and Knight, 1977; Kolstad and McGetchin, 1975; Smith and Shaw, 1975) of thermal evolution modeling of plutons show that a magma body about 10 km in radius (of either spherical or cylindrical geometry) will be solid at depths above 6 km in the order of a million years or substantially less, and that 90% of the initial magmatic heat will be stored in the rocks and fluids in the vicinity — probably mainly as HDR. Although heat may be efficiently transferred in hydrothermal systems, it is probably safe to assume that the bulk of this heat is stored as HDR. Consequently, the magnitude of the heat stored in the HDR part of igneous-related systems may be assumed to be the energy originally stored in the magma itself. It is also noteworthy that there is now observational evidence (Simmons and

Richter, 1976; Aamodt, 1976) to support earlier speculation (Kennedy, 1970) that the rock environment near young evolving magma chambers may be relatively impermeable due to the self-sealing or annealing effects of mineralization occurring near the pluton as it cools. The aging of igneous-related geothermal systems proceeds as heat is transferred to the surface by both conduction and convection. Convection will occur principally in hydrothermal activity over the pluton, but it also can occur by groundwater motion in country rocks surrounding the pluton (Norton and Knight, 1977) if permeabilities exceed about 1 microdarcy.

Table 5.4.II is a summary of available data and status of knowledge on the 14 sites listed earlier. The table contains a suggested classification of various volcanic and igneous-related sites, a tabulation of the basement rock type index, and an estimate of the quality of existing knowledge regarding each site.

TABLE 5.4.II Summary of Selected Volcanic and Igneous-Related Potential HDR Sites

	Site	Volcanic System Characteristics: Type of Volcanic System (1)	Log V (km^3)	Log t age (yr)	Basement Rock Index (2)	Status of Available Knowledge (3): Surface Geology	Age Dating	Petrol-ogy	Geo-chem	Seismo	Gravity	Mag	Heat Flow
Existing ERDA HDR Sites	Valles Caldera	A1	3.55	5	1	1	1	2	2	3	1	2	2
	Coso	A2	2.8	4.6	1+	1	1	2	2	2	2	2	2
Sites Recommended by HDRAP	Long Valley	A1	3.4	5	1	1	1	2	2	1	1	2	2
	San Francisco Peaks	A5,A2,B3	3.1	5.3	1(4)	1	1	2	2	3	2	2	3
	Shasta	A5	2.5	2.6	2.5	1	2	2	3	3		2	3
	Medicine Lake	A3	2.5	3	3	1	1	1	2	3	2		3
Other Sites with HDR Potential	Yellowstone	A1	4.2	4.9	2.5	1	1	2	2	1	1	2	1
	Island Park	A1	4.5	6.1	2.5	1	2	2	2	1	1	2	1
	Mineral Mtns	A2	3.1	5.75	1	2	2	2	2				
	Clear Lake	A2,A6	3.2	5	3	1	1	2	2	2	1		
	Lassen	A4,A5	2.6	1.8	2.5	2	2	2	2	3	2		
	Blackfoot	A4	2.0	4.7	3.5	2	2	3	3	3	2		
	Edgecumbe	A5	2.4	4	3	2	2	2	2	3	3		
	Mono Craters	A2	2.3	3	1	2	2	2	2				

Definitions and footnotes:

(1) Types of Volcanic Systems

A. Silicic volcanic systems
1. Large calderas
2. Large dome clusters
3. Small calderas
4. Small dome clusters or single domes
5. Andesite stratovolcanoes with silicic vents
6. Other

B. Basic volcanic systems
1. Calderas of shield volcanoes
2. Andesite stratovolcanoes
3. Large vent clusters
4. Small vent clusters and single vents
5. Other

(2) Basement Rock Index
1. Granitic or plutonic
2. Precambrian or Paleozoic metamorphics
3. Mesozoic folded metamorphics
4. Paleozoic or Mesozoic sediments
5. Cenozoic volcanics or sediments

(3) Status of Knowledge
1. Detailed data available
2. Adequate for slim hole drilling
3. Inadequate

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5.5 Regional Sites Recommended by HDRAP for Future Investigation

Based on available geological and geophysical data, the four localities described below were recommended by HDRAP as prime regional sites to be considered for future detailed assessment of their HDR geothermal energy resources. Consideration of these four areas was limited to the technical or scientific desirablity of the site. Yellowstone, Lassen, and Crater Lake, although indicated on Fig. 5.4.2, have been excluded from serious consideration because they are National Parks.

In addition to seeking the most promising and likely locations for finding rocks suitable for eventual HDR energy extraction, two considerations were foremost in the selection process -- first, the need to broaden the HDR resource base beyond its present concentration in areas of young silicic volcanism (Valles and Coso, both Category 1A sites), and secondly, to select areas that might be representative of other types of potentially important HDR sites so that the eventual magnitude of the total resource base might be more accurately assessed. The list of localities currently recommended for assessment and possible development include:

(A) Long Valley, CA (1A1)
(B) San Francisco Peaks, AZ (1B3; but also, 1A5 and 1A2)
(C) Medicine Lake Highland, CA (1A3)
(D) Mt. Shasta, CA (1A5)

Long Valley, CA, is a large, young center of silicic volcanic activity, with much in common geologically to the Valles Caldera and Coso Area HDR sites. However, in spite of this similarity, because of the excellent available data base and very high likelihood of finding potentially usable HDR, the HDRAP recommended that Long Valley be given first priority in future site development. San Francisco Peaks, near Flagstaff, AZ, is an area of copious basaltic and andesitic volcanism but in which very young silicic intrusions are thought to have carried and deposited heat in the upper crust. This area may be representative of other localities within the western U.S. where basaltic volcanism has occurred in the recent geologic past. Medicine Lake Highland and Mt. Shasta, in the southern part of the Cascade Range within northern California, constitute important examples of the volcanic centers associated within large-scale tectonic features, namely subduction zones typical of the entire circum-Pacific margin, including the Aleutian chain. The large andesitic volcanic centers of Washington, Oregon, California, and Alaska are in several important respects represented by those sites. The HDRAP recognizes that each possible HDR site has its own geological characteristics, but it is felt this list of possible future sites covers a much broader part of the potential HDR resources than is currently represented in the HDR program.

5.5.A Long Valley, CA

Introduction. The Long Valley Caldera and its associated geothermal system have been intensely studied over the past four years (1972-1975) as part of the U.S.G.S. Geothermal Research Program, and it is at present probably the most thoroughly studied large geothermal system in the western U. S. The results of these U.S.G.S. studies were recently published in the Journal of Geophysical Research, v. 85, no. 5. A comprehensive history of the volcanic and tectonic evolution of the Long Valley area has been prepared from detailed geologic mapping, supplemented by abundant radiometric dating (Bailey, 1974; Bailey et al., 1976). A coherent model of the subsurface configuration and internal structure of the caldera has been constructed from gravity, aeromagnetic, and seismic refraction surveys (Kane et al., 1976; Hill, 1976), and a preliminary understanding of the geothermal system to depths of 1 to 2 km has been gained from heat flow studies (Lachenbruch et al., 1976a, 1976b; Sorey and Lewis, 1976), water chemistry studies (Mariner and Willey, 1976), and electrical resistivity, audiomagnetotelluric, self potential, and seismic noise surveys (Stanley et al., 1976; Hoover et al., 1976; Iyer and Hitchcock, 1976). Also, from seismic monitoring of the area (Steeples and Pitt, 1976; Steeples and Iyer, 1976; Hill, 1976) an anomalous low-Q region, thought to be a partially molten residual magma chamber, has been identified.

Continuing work includes (1) detailed studies of the mineralogy and chemistry of volcanic rocks to define more completely the conditions and mechanisms of differentiation of the magmatic system and (2) hydrologic studies and geochemical studies to understand better the deep circulatory system. Within the coming year, deep seismic sounding may be undertaken in the area by the Consortium for Continental Reflection Profiling (COCORP). An exploratory drill hole very recently drilled in the southeast moat by Republic Geothermal, Inc. in a joint venture with the City of Burbank revealed moderately low temperatures.

Geologic Setting. Long Valley caldera is a 30- by 20-km elliptical depression located on the east front of Sierra Nevada at the north end of Owens Valley, on the western edge of the Basin-Range Province, (see Fig. 5.5.1). Volcanism in the area began 3.5 m.y. ago at the climax of uplift of the Sierra Nevada and has been intermittently continuous almost to the present. The most recent volcanic eruptions occurred 650 $\pm$ 200 yr ago (i.e. between 1100 and 1500 AD), and the frequency of previous pyroclastic eruptions suggests that a similar eruption can be expected in the future; hence the area is by definition an active volcanic zone.

The caldera is transected (Fig. 5.5.2) by a main eastern frontal fault of the Sierra Nevada, which has been active for the past 3 m.y. in both pre- and post-caldera time. Displacement on the fault in the past 700,000 yr, since collapse of the caldera, has been in excess of 300 m and earthquakes and ground breaking have occurred along it in historic time. Thus the caldera is located in a zone of active tectonism, as well as active volcanism, at the boundary of the Basin-Range and Sierra Nevada provinces.

Volcanism. The basement rocks in the vicinity of Long Valley consist mainly of Jurassic and Cretaceous granitic plutons of the Sierra Nevada batholith, which locally enclose roof pendants of Paleozoic metasediments and Mesozoic metavolcanics, Fig. 5.5.2. Resting on these older rocks on an early Tertiary erosion surface of low to moderate relief are late Tertiary volcanic rocks, mainly trachybasalts and trachyandesites 3.5 to 2.6 m.y. old and as much as 200 m thick. These lavas constitute the southern part of a much larger field of mafic to intermediate volcanics that extend many tens of kilometres north of Long Valley; and although they locally include accumulations of rhyodacite, the distribution of centers suggests that they are not directly related to the Long Valley center of activity. There is no evidence of a long pre-caldera history of mafic or intermediate volcanism or a thick accumulation of pre-caldera volcanic rocks at Long Valley Caldera, as there is at Valles Caldera.

The episodic volcanism directly associated with the Long Valley magmatic system began at about the time of inception of faulting along the East Sierra escarpment. The principle eruptive units include (1) the rhyolites of Glass Mountain (1.9 to 0.9 m.y. old), a 1000-m-thick accumulation of dome flows, and tuffs, exposed on the northeast rim of the caldera, (2) the Bishop Tuff (0.7

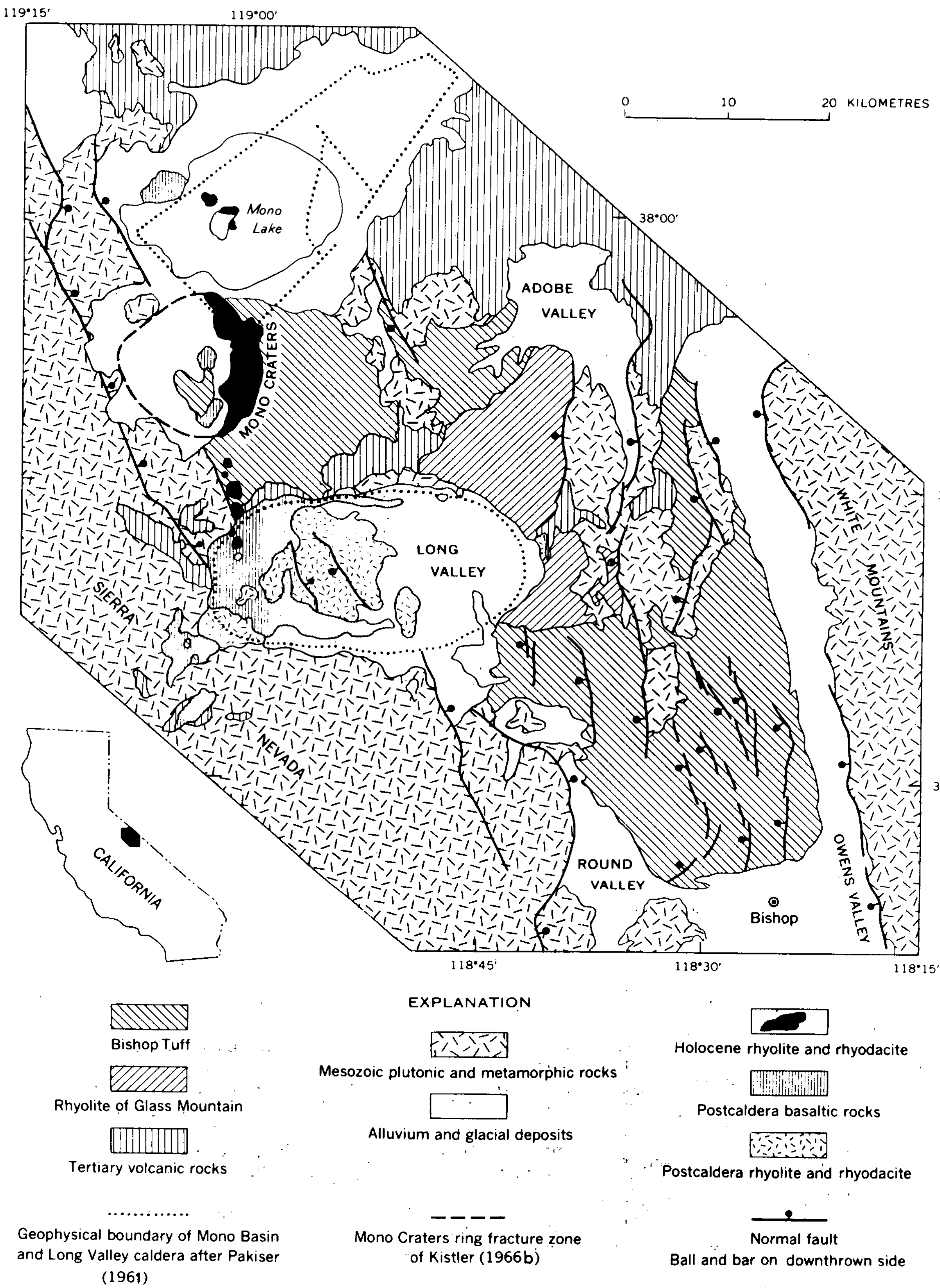

Figure 5.5.1 Index map and generalized geologic map of the Long Valley-Mono Basin area.

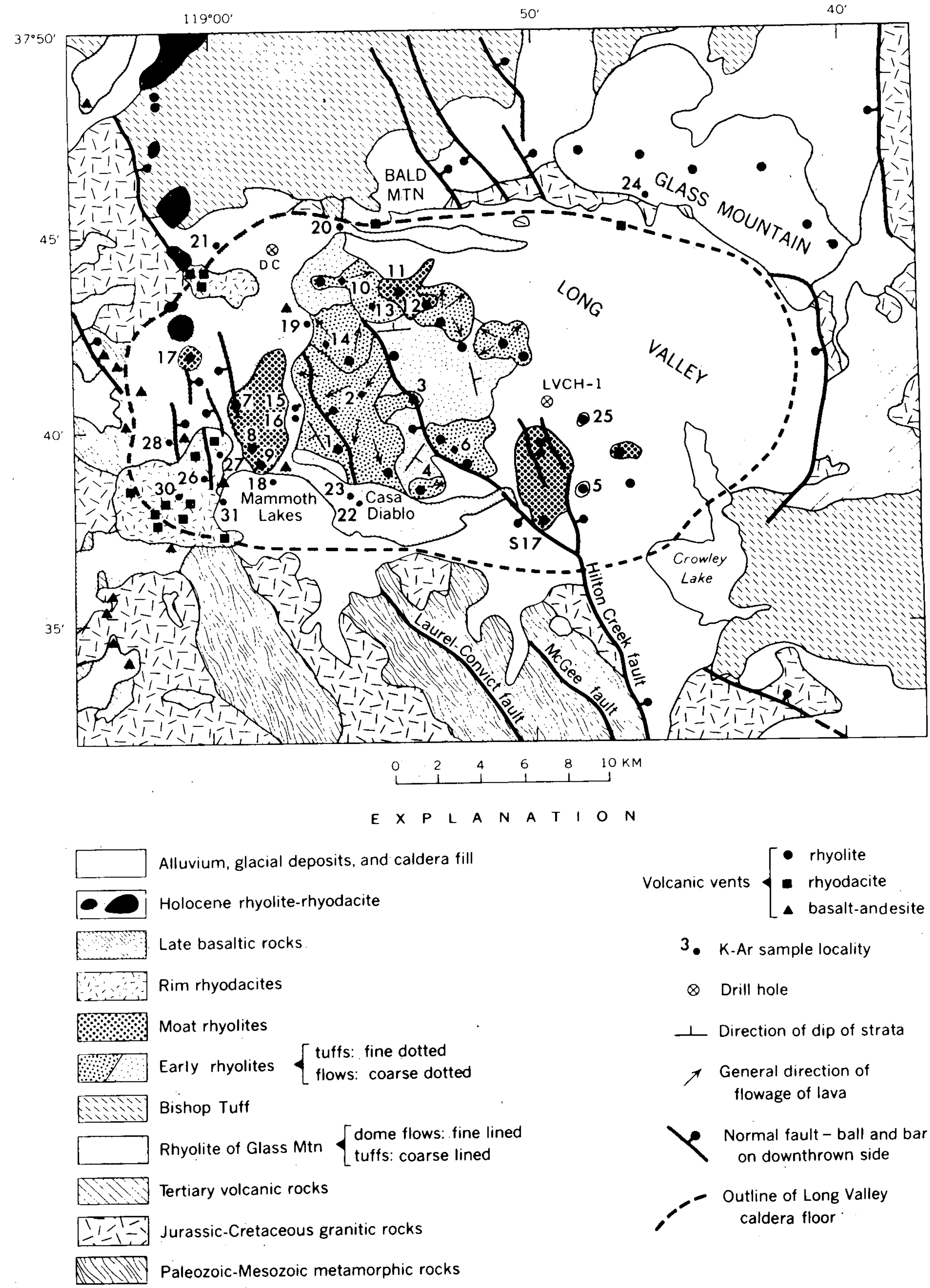

Figure 5.5.2 Generalized geologic map of Long Valley Caldera.

m.y. old), the caldera-forming ash-flow deposits, which occur buried within the caldera, as well as outside as extensive outflow sheets, and (3) post-caldera rhyolites and rhyodacites (680,000 to 100,000 yr old), confined within the caldera. These latter intracaldera rocks include (a) an early group of aphyric to sparsely porphyritic high-silica rhyolites that erupted synchronously with resurgence of the caldera floor (680,000 to 640,000 yr ago), (b) three groups of coarsely porphyritic low-silica rhyolites that erupted peripheral to the resurgent dome in the caldera moat (0.5, 0.3, and 0.1 m.y. ago), and (c) a group of coarsely porphyritic hornblende-biotite rhyodacites that erupted on the caldera rim and margins (300,000 to 50,000 yr ago). Field and preliminary petrochemical data suggest that this entire suite of rhyolites and rhyodacites erupted from a chemically zoned magma chamber from progressively greater depths in the range of 5 to 8 km. Evidence from seismic refraction and teleseismic P-wave delays suggests that the chamber may still be partially molten at depths from 8 to 25 km.

Superimposed on the episode of volcanism related to the Long Valley Caldera are two younger episodes (1) a trachybasaltic episode, erupted 200,000 to 13,000 yr ago from an <u>en echelon</u> fracture system parallel to the Sierra Nevada front and extending 50 km from Devil's Postpile through the west moat of Long Valley Caldera to the north shore of Mono Lake, and (2) a rhyolitic episode, erupted 12,000 to 720 yr ago from the Mono and Inyo Craters. Petrochemical and structural analogies with the Glass Mountain rhyolites, which erupted on an incipient ring fracture related to the Long Valley magma chamber, and coincident gravity and magnetic anomalies associated with Mono Craters ring fracture zone (Kistler, 1966) suggest that the Mono Craters erupted (or possibly are erupting) from a modern subjacent magma chamber. The Inyo Craters, which are aligned along an apparent north-south fissure between the Mono Craters and the west moat of Long Valley Caldera, consist of a physical mixture of coarsely porphyritic rhyodacite like that associated with Long Valley and sparsely porphyritic obsidian like that of the Mono Craters -- a relationship that suggests mixing of magmas from the two chambers.

<u>Subsurface Structure</u>. Gravity (Fig. 5.5.3) and seismic refraction studies (Fig. 5.5.4) of Long Valley Caldera show with remarkably good agreement that the depth to basement is 2.5 to 3 km in the northern and 1 to 2 km in the southern part of the caldera, suggesting that the cauldron block tilted to the

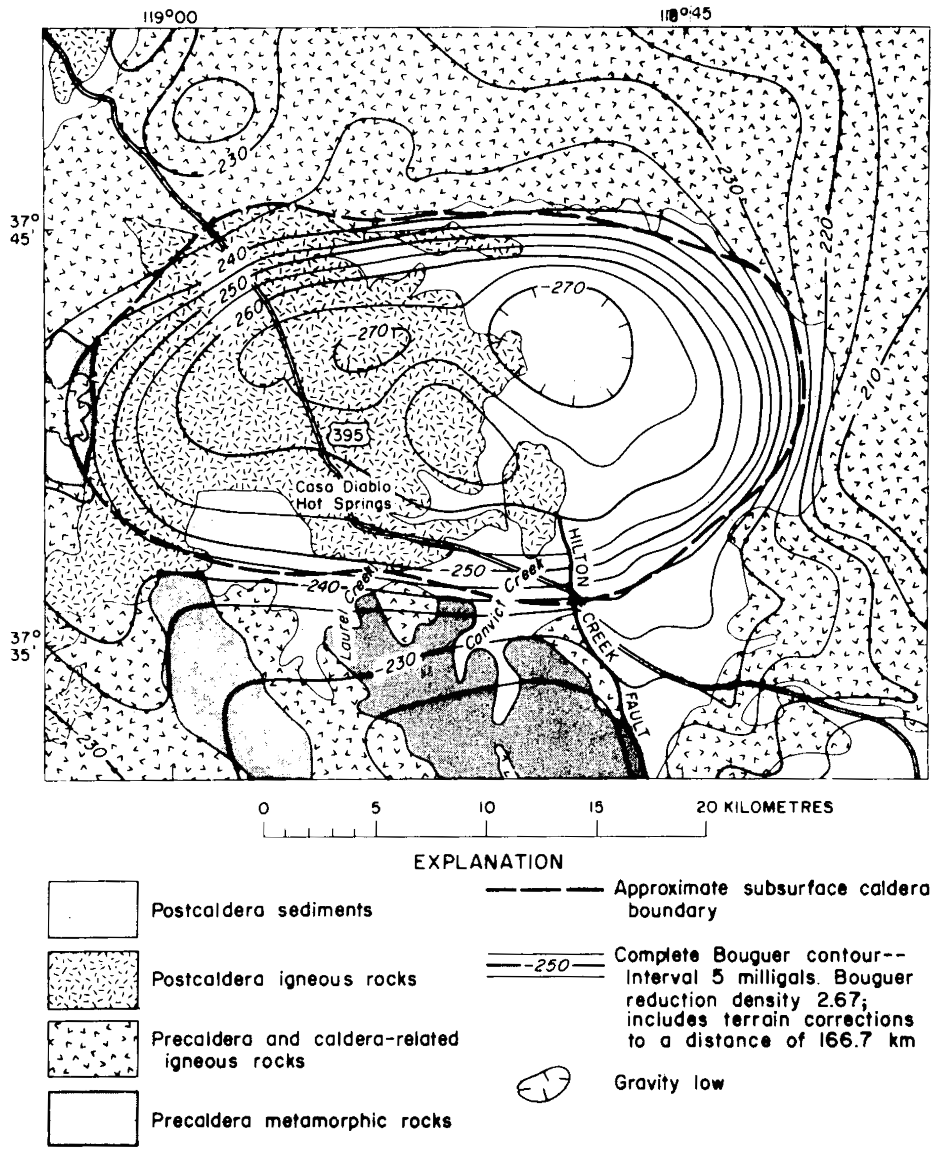

Figure 5.5.3 Combined generalized geology and complete Bouguer gravity map of Long Valley Caldera and vicinity. Geology is generalized from R. A. Bailey (1974). Gravity is modified from Oliver and Robbins (1973).

north during subsidence. Gravity and seismic refraction studies confirm the presence of a broad resurgent dome with 0.5 to 1 km structural relief in the west central part of the caldera. Although Bishop Tuff is not exposed in the caldera, a layer with a seismic velocity of 4.0 to 4.4 km/sec tentatively identified as densely welded Bishop Tuff rises from a depth of 2 km in the moat to 1 km beneath the crest of the resurgent dome.

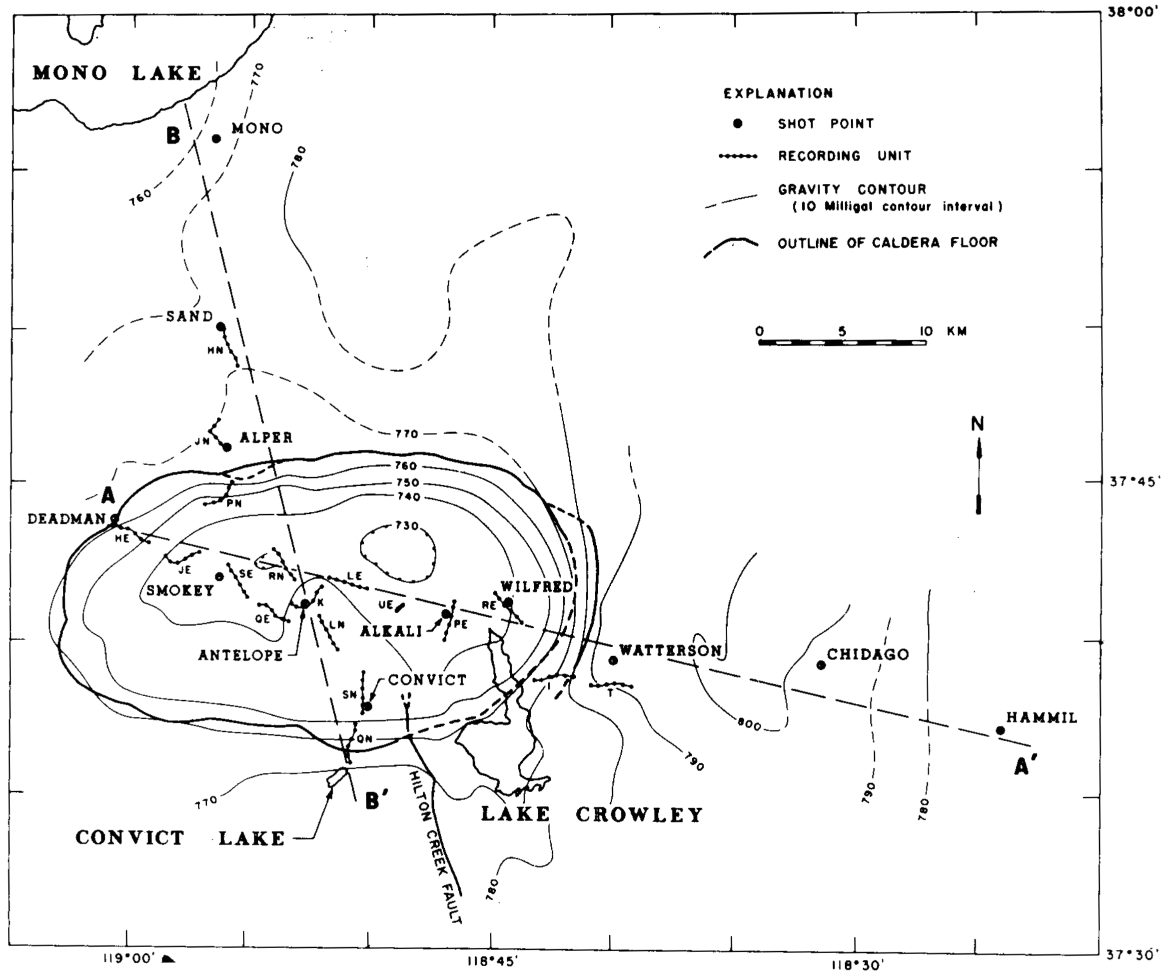

Figure 5.5.4(a) Map showing locations of shot points and recording units with respect to the outline of the caldera floor and 10-mgal gravity contours. Caldera faults are closely associated with caldera floor outline (see Bailey et al., 1976).

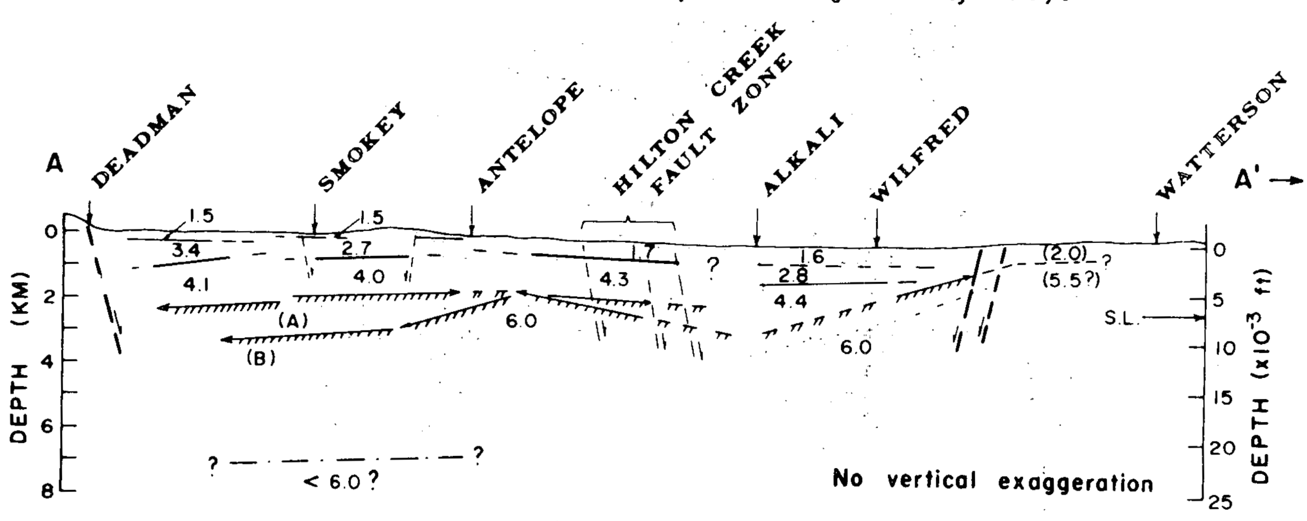

Figure 5.5.4(b) Cross section showing P-wave velocity structure under profile AA' of Fig. 5.5.4 (a).

Comparison of seismic refraction and gravity models indicates local accumulations in the moat of abnormally low-density materials that probably represent buried cones of coarse pumice around early post-caldera rhyolite vents on the ring fracture zone. A prominent magnetic high (Fig. 5.5.5) in the east central part of the caldera is attributable to a rock mass at a depth of 1 km, which is interpreted as an abnormal thickness of Bishop Tuff that accumulated in a pre-caldera topographic trough between the Hilton Creek fault and the

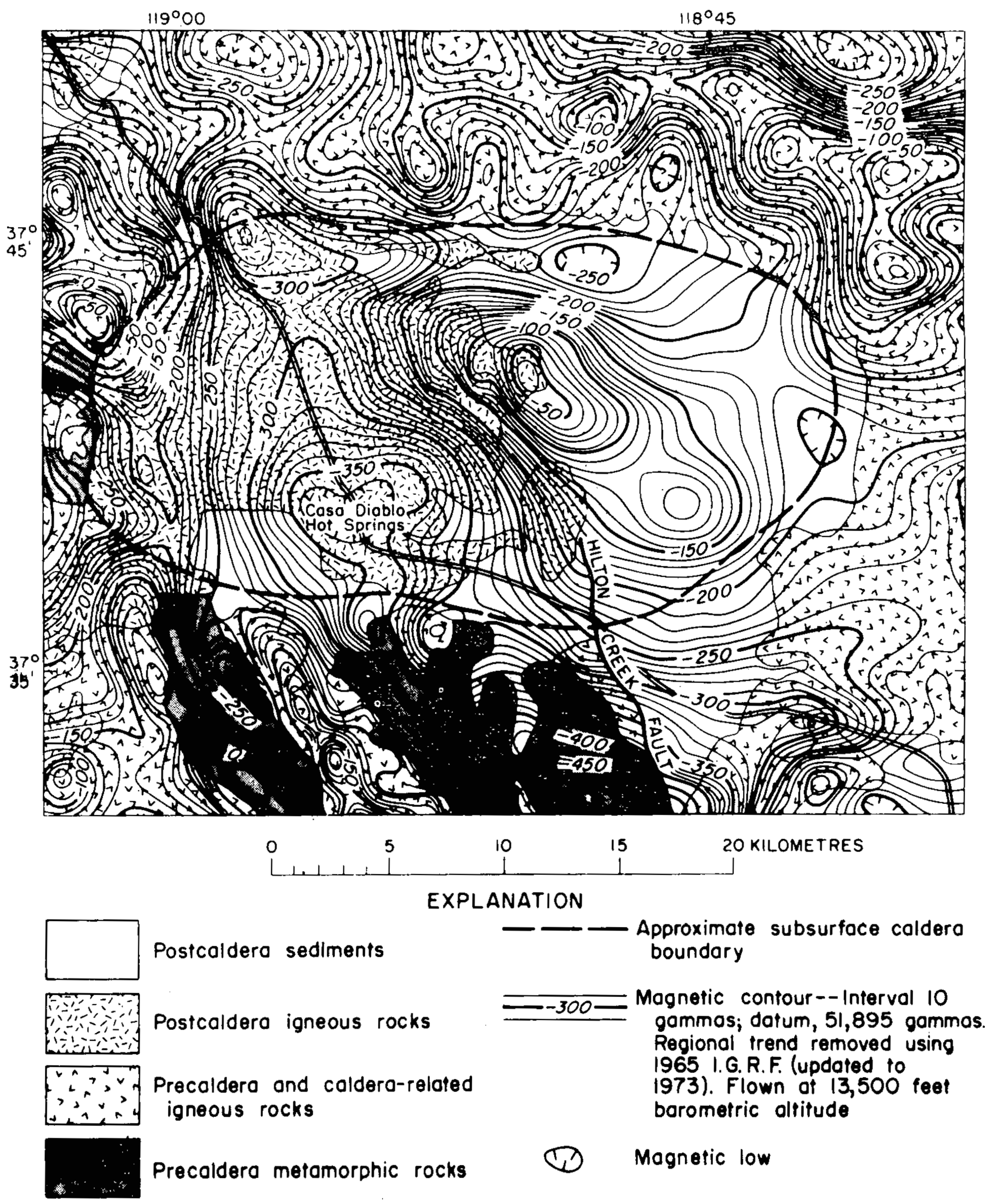

Figure 5.5.5 Combined generalized geology and high-level residual magnetic intensity map of Long Valley area.

Glass Mountain rhyolite center. A prominent north-northwest trending magnetic low transecting the western part of the caldera is thought to be due in part to demagnetization associated with hydrothermal alteration in the vicinity of Casa Diablo Hot Springs, but the linearity and continuity of this low suggests that it is in part attributable to non-magnetic Paleozoic carbonate rocks of the Mount Morrison roof pendent, which probably continue across the cauldron block in the basement.

Thermal Anomalies. Identification of thermal anomalies associated with the Long Valley magma chamber is complicated by the location of the caldera on the boundary between the Sierra Nevada and Basin-Range Provinces, across which there is a regional thermal gradient of at least 1 HFU in 30 km. On the basis of rather limited data, there appears to be little or no thermal anomaly relative to the Basin-Range norm near the eastern edge of the caldera and an anomaly of 2.75 HFU above the Sierra norm near the western edge of the caldera, Figs. 5.5.6 and 5.5.7. This relation, together with the fact that practically all the post-caldera volcanism has been confined to the western half of the caldera, has led to speculation that (1) the eastern half was underlain by a sill-like tongue of magma that was completely drained during eruption of the Bishop Tuff, and (2) that the main magma chamber, more circular in plan, is located beneath the resurgent dome in the west-central part of the caldera -- an explanation which, incidentally, also accounts for the unusual elliptical shape of the caldera.

Thermal calculations based on simple heat conduction models indicate that an isolated magma chamber of the size inferred beneath the caldera would have crystallized completely in 700,000 yr. Consequently, the upper crustal magma chamber must have been repeatedly replenished with heat from deeper magmatic sources in order to have maintained volcanism over the 2 m.y. life span of the system.

Geologic constraints on the age of the magmatic system associated with the Mono Craters ring fracture indicate that it is younger than 700,000 yr and has been a source of volcanism for the past 12,000 yr. Heat flow data from a drill hole at Aeolian Buttes, in the center of the Mono structure, show that heat from the subjacent magma chamber, if it exists, has not yet affected near-surface temperatures. Thermal modeling of the inferred chamber indicates that its

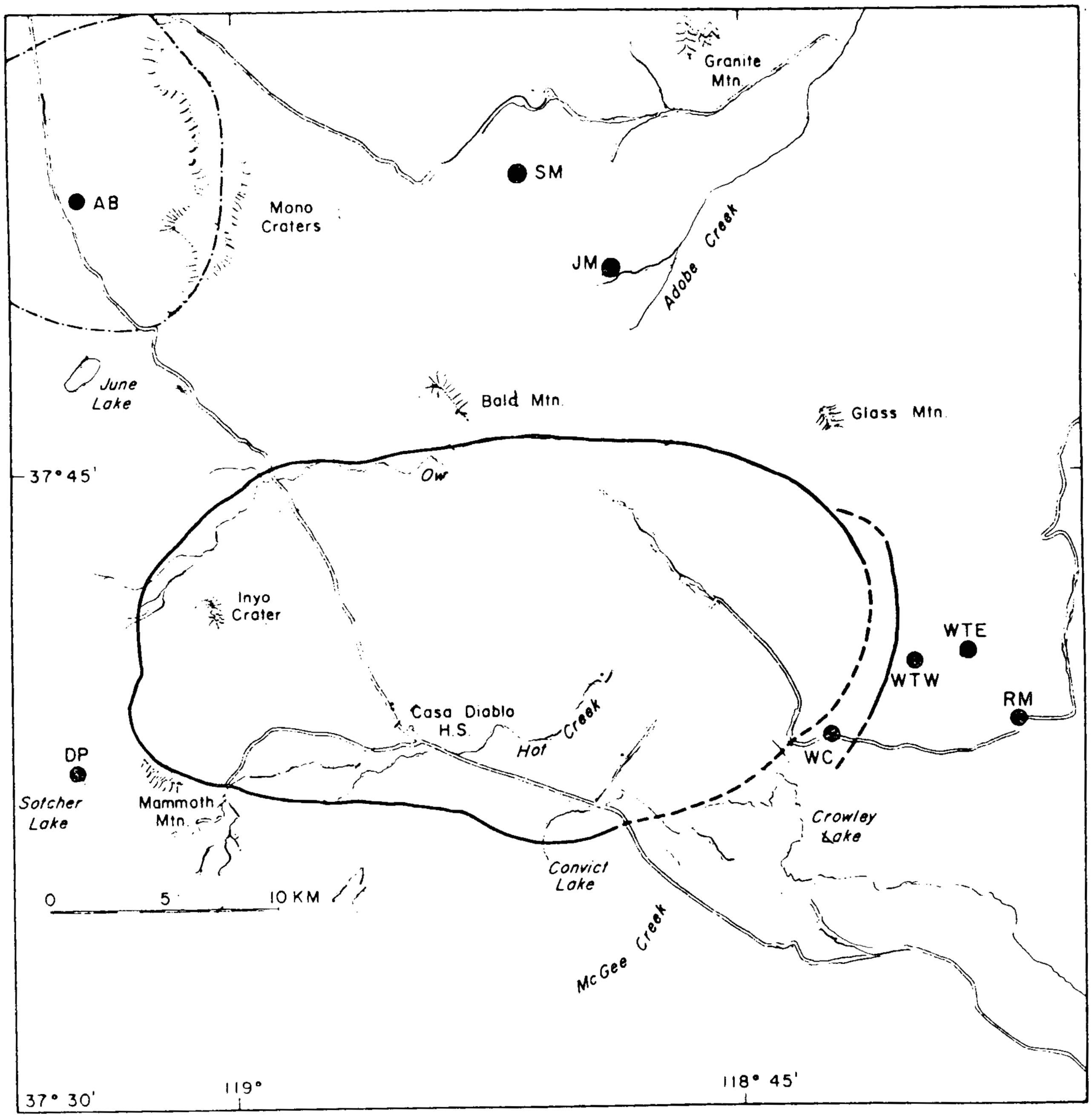

Figure 5.5.6 Sketch showing the location of close-in heat flow stations relative to the caldera rim and other major physiographic features. Chain-dotted line at upper left outlines the ring fracture zone of Kistler (1966). The small dots inside the caldera show the locations of heat flow and hydrological data discussed by Lachenbruch et al. (1976a).

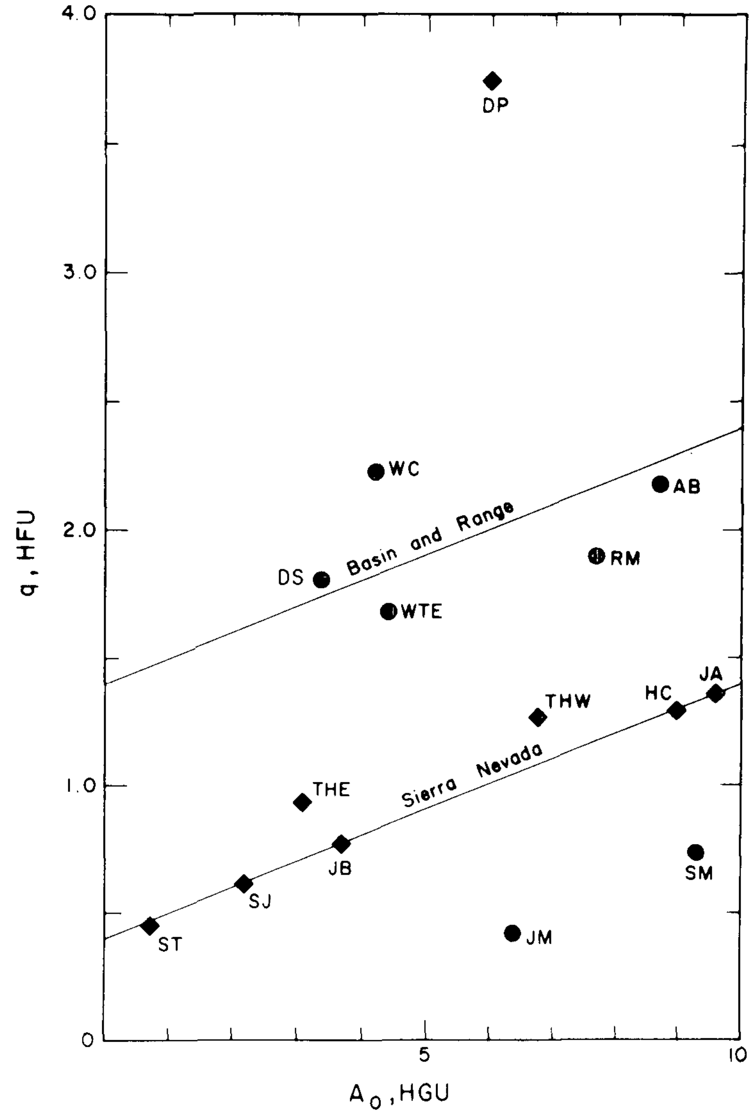

Figure 5.5.7 Heat flow versus heat production for granitic rocks in the region surrounding Long Valley. Square symbols are identified with the Sierra Nevada physiographic province; circles, with the Basin and Range Province. The straight lines represent previously determined relationships for the two provinces.

top must be at depths of the order of 8 to 10 km, unless it has risen rapidly in recent years, in which case it could be as shallow as 2 km.

Hydrothermal System. Hydrothermal activity in Long Valley Caldera is manifested mainly as hot springs and thermal springs (180°C), most of which are in the south and southeast moat and localized along young faults and fractures related to recently rejuvenated Sierra frontal faults. Fumaroles also occur locally but are confined to faults within the medial graben of the resurgent dome. Evidence that surface hydrothermal activity was formerly much more extensive, as well as more intensive, is found in the form of widespread fossil fumaroles, silicious sinter deposits, and acid alteration in lake sediments. The age of these sediments suggests that surface hydrothermal activity reached a climax about 300,000 yr ago and has declined because of one or a combination of several possible causes, including (1) reduction of porosity of the sediments by silicification, argillization, and zeolitization, (2) draining of the caldera lake with consequent lowering of the water table, and (3) decline in temperature of the main heat source. Although surface hydrothermal activity is almost entirely absent in the north and west moats, it is apparently masked there by shallow ground water flows from the Sierra Nevada. Hydrologic and thermal data from 30 shallow drill holes suggest that the system is recharged along the caldera margins, particularly in the west, and that the waters are heated by deep circulation eastward around the resurgent dome and eventually emerge in the low southeast moat, rising along faults and entering into shallow aquifers. Deep electrical soundings in the southeast moat indicate no major hot water reservoirs within 2 km of the surface. The geothermal gradient in a 305-m drill hole on the east flank of the resurgent dome, however, suggests that reservoir temperatures are attained at about 1 km. Geochemical temperatures of the hot springs suggest a hydrothermal resource temperatures of the order of 200°C. The thermal waters are typical of a hot water system -- alkali-chloride-bicarbonate waters high in B, As, and SiO_2. Electrical resistivity data (Fig. 5.5.8) show lows are associated with known fracture systems, so it is inferred that the subsurface flow of hot water is being controlled by faults, principally those related to the regional Sierran fault system.

Potential HDR Resources. As an aid to the selection of areas for resource assessment purposes, the following three different settings or terranes are described: (1) the caldera moat, (2) the resurgent dome, and (3) extracaldera areas.

(1) The caldera moat. The caldera moat, particularly the southern, eastern, and northern sectors, has generally low relief and good accessiblity. These areas are underlain mainly by sediments and pyroclastic rocks, locally intensely silicified to depths of 50 m and commonly argillized or zeolitized to depths of at least 300 m. In the north and south moat thin basalt flows and a few rhyolite flows are exposed at the surface but can be avoided by judicious

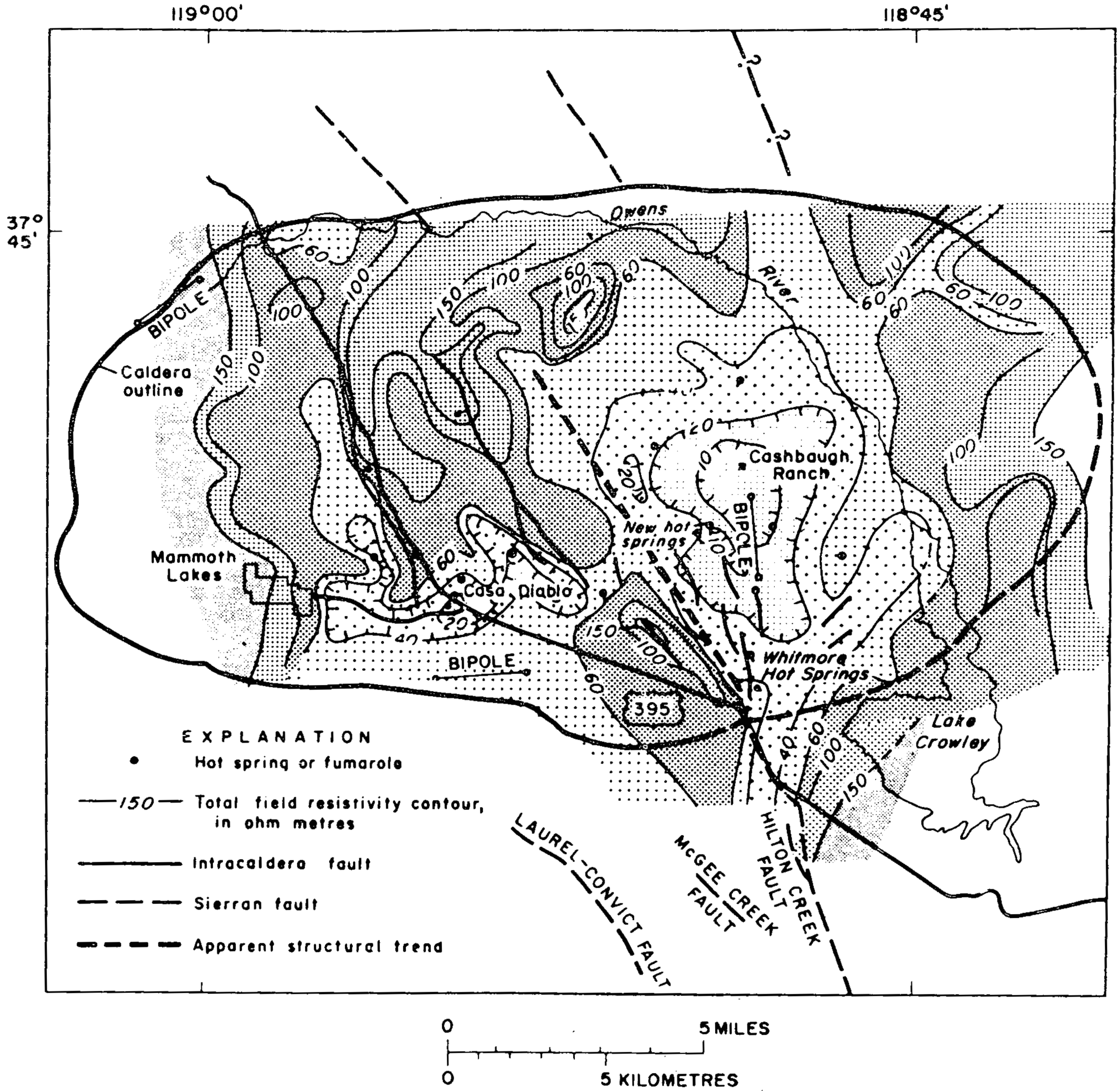

Figure 5.5.8 Composite total field resistivity map for Long Valley Caldera compiled by using data from bipoles 2, 3, and 4.

site selection. Electrical resistivity surveys indicate (Fig. 5.5.8) that perched hot-water aquifers, probably fed from depth by faults and other fractures, are present at depths to 2 km. Seismic refraction studies suggest that below 2 km densely welded Bishop Tuff is to be expected. Muffler and Williams (1976) have suggested that pervasively fractured Bishop Tuff is a likely reservoir rock within the caldera.

In the western sector of the moat, dense forests, rough topography, and few roads severely limit accessibility. In addition, the west moat is underlain by an estimated 100 to 200 m of jointed and brecciated basaltic lavas, which in the past have posed drilling problems with caving and loss of circulation being the most serious. Below these basaltic rocks drilling in rhyolite tuffs and eventually Bishop Tuff should be less difficult. However, little is known of the complexities of the stratigraphy and structure in the west moat. Numerous faults are to be expected, because both the Hartley Springs fault and the Silver Lake fault (major Sierra frontal faults) project into the western sector; the faults are the locus of most volcanism in the sector.

(2) Resurgent dome. Although topographically rugged and moderately heavily forested, many parts of the resurgent dome are relatively accessible by numerous, moderately wide, though unimproved, logging and fire-access roads. On the basis of surface mapping and seismic refraction data, the dome is underlain to a probable depth of 500 to 1000 m by interlayered rhyolite tuffs and flows, below which the Bishop Tuff should be encountered. Within the medial graben, faults are abundant and complex, and along some, particularly in the southern part of the graben, intense acid hydrothermal alteration and active fumaroles suggest that they are open to considerable depths. If Union Oil Company's experience in drilling the Valles Caldera resurgent dome is indicative, the Long Valley medial graben may be among the more promising parts of the caldera for commercial steam production (a large hydrothermal resource). A 305-m-deep hole drilled by the U.S.G.S. on the east edge of the dome showed a geothermal gradient of 175°C/km. Another hole to 200 m on the east flank of the dome showed a temperature gradient of 650°C/km before becoming isothermal at 110°C in the bottom 25 m.

(3) Extracaldera areas. For purposes of HDR assessment, the area between Long Valley Caldera and the Mono Craters, in the general vicinity of the Inyo Craters chain, should be of interest. The Long Valley magma chamber and the inferred Mono Craters chamber are within 8 km of one another in this area, and along the base of the Sierra Nevada on the west side of the area, magma from both chambers has apparently migrated laterally at depth and erupted at the surface to form the Inyo Craters. Densely welded Bishop Tuff, beneath a thin cover of Mono Craters airfall pumice, underlies most of the area to depths of possibly up to 500 m according to seismic refraction studies. Below this,

200 to 300 m of Tertiary andesites may be encountered locally above the Mesozoic plutonic rocks of the Sierra Nevada batholith. There are sites within this area, however, where drilling could be initiated in plutonic rocks. Road access in the area is good. Although geothermal gradients in the area are expected to be high, it should be pointed out that a 124-m hole drilled by the U.S.G.S. at Aeolian Buttes, in the center of the Mono Craters structure, showed a geothermal gradient of only 37°C/km, and a commercial exploratory hole to 1240 m at Mono Lake, on the north side of the structure, showed a gradient of 25°C/km in basement rock, about normal for the Basin-Range-Sierra Nevada transition.

The high heat flow (DP in Fig. 5.5.6) near Solcher Lake is very suggestive of an HDR areal site that might warrant further investigation.

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5.5.B San Francisco Peaks, AZ

Introduction. This section provides preliminary data for evaluation of the possible occurrence of HDR under the San Francisco volcanic field. The data summarized below suggest that there is a reasonable prospect of finding young, hot igneous rock in the subsurface east of the San Francisco Mountain. Slightly older plutonic rocks may underlie a belt of rhyolitic domes in the western part of the volcanic field. Geophysical reconnaissance and heat flow investigations would be extremely valuable adjuncts to the continuing geologic investigation of this area.

Active volcanism has continued from Pliocene to late Holocene time in the San Francisco volcanic field, which is located on the Colorado Plateau near its southern margin in north-central Arizona (see Fig. 5.5.9). The volcanic

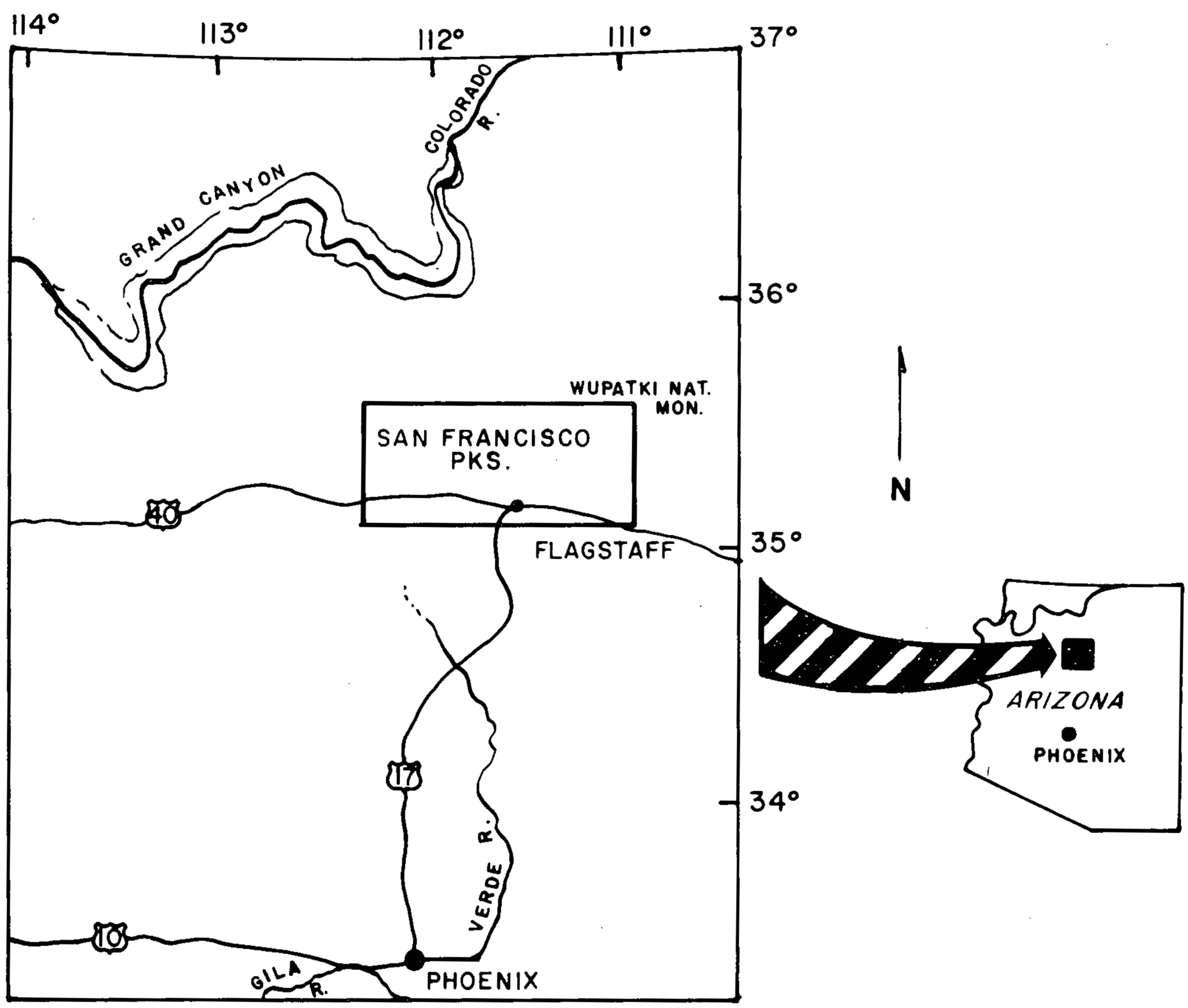

Figure 5.5.9 Location map of San Francisco Peaks, Arizona.

rocks compose an apparently consanguineous compositional spectrum that ranges from alkali-olivine basalt to rhyolite and is transitional between alkalic and calc-alkalic suites. Generally, as outlined below, centers of silicic volcanism have developed progressively farther east-northeastward with time; the youngest rhyolitic eruptions and the youngest basaltic eruptions, including the 910-yr-old Sunset Crater eruption, were concentrated together in the eastern part of the volcanic field.

Distribution and Geochronology of the Volcanic Rocks. Bimodal (basaltic and dacitic to rhyolitic) volcanism began north of the Mogollon Rim about 6 m.y. ago with extrusion of widespread basalt flows; silicic eruptions occurred at Bill Williams Mountain in the westernmost part of the volcanic field (Fig. 5.5.10). Most eruptive activity has been concentrated, however, within the

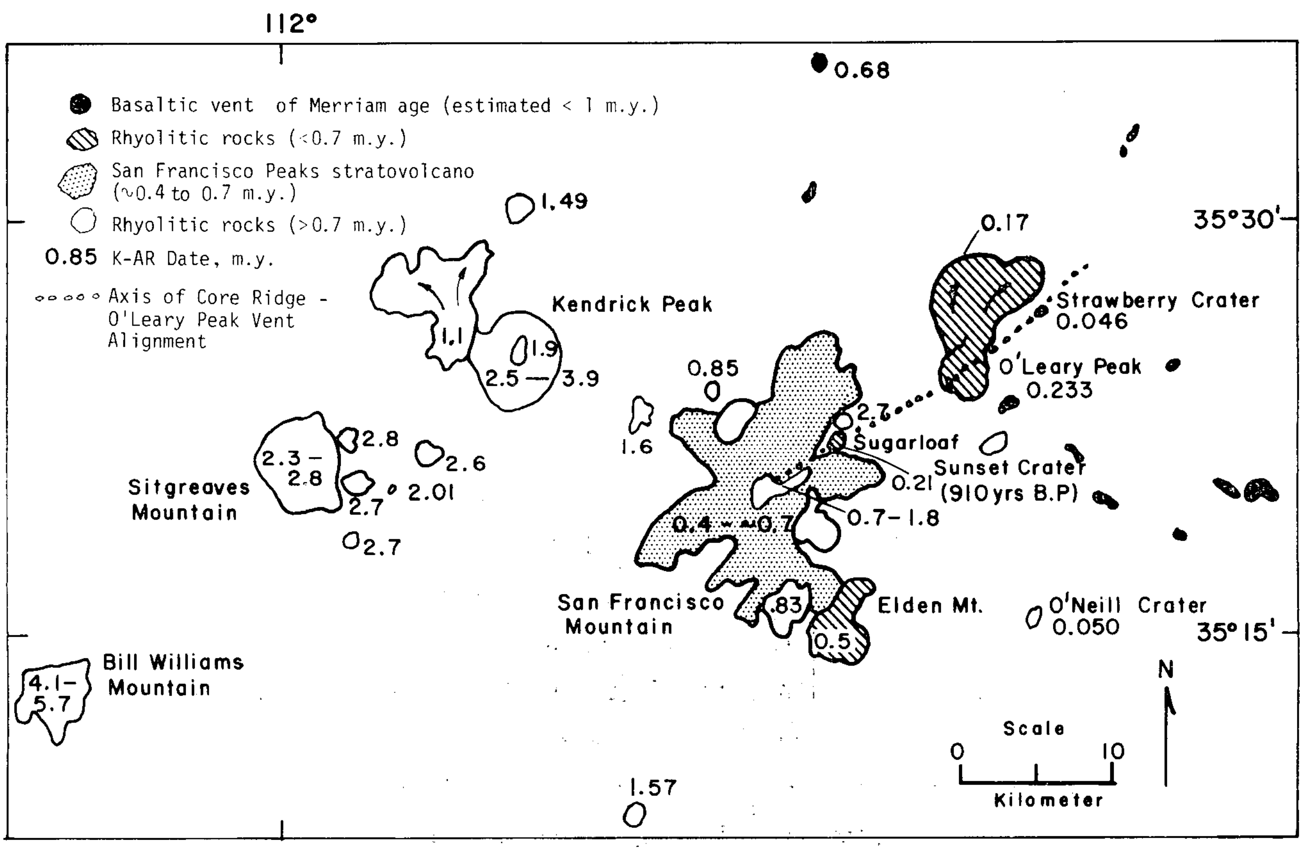

Figure 5.5.10 Distribution and ages of rhyolitic rocks, San Francisco Mountain stratovolcano, and youngest basalt vents of the San Francisco volcanic field, Arizona. K-Ar ages determined mainly by P. E. Damon and M. Shafiqullah (Univ. of Arizona) and E. H. McKee (U.S. Geological Survey).

past 3 m.y. With one exception, rhyolitic eruptions between 2 and 3 m.y. in age were confined to the vicinity of Kendrick Peak and Sitgreaves Mountain in the western part of the volcanic field, where a belt of rhyolitic domes formed. A strong gravity low (Fig. 5.5.11) coincides with the Kendrick-Sitgreaves rhyolitic belt. Between 2 m.y. and about 700,000 yr ago, rhyolitic eruptions were concentrated in the central part of the field from Kendrick Peak eastward through the San Francisco Mountain area. Between 400,000 and 700,000 yr ago a composite cone, San Francisco Mountain, composed of interlayered lava flows and pyroclastic deposits of basaltic andesite, andesite, dacite, and minor basalt, was the locus of intermediate to silicic eruptive activity. Contemporaneous basalts of the Tappan age group (approximate age of 700,000 to 200,000 yr) were erupted from numerous vents north and east of San Francisco Mountain. (Data are incomplete west of San Francisco Mountain.) More recently, rhyolitic eruptions, ranging from about 250,000 to 50,000 yr in age have occurred east of San Francisco Mountain. These include the Sugarloaf rhyolite dome (210,000 yr), the O'Leary Peak rhyodacite domes (233,000 yr) and related flows (169,000 yr), and the dacite and rhyodacite vitrophyre plugs of Strawberry (46,000 $\pm$ 16,000 yr) and O'Neill (50,000 $\pm$ 14,000 yr) Craters (see Fig. 5.5.10). Basaltic vents of Merriam age (estimated 100,000 yr) and the 910-yr old basalt vent that formed Sunset Crater occur near those silicic vents as well as to the north and east of them (Fig. 5.5.10).

In addition to the age relationships, which, in a search for hot subsurface rock, focus attention on the eastern part of the volcanic field, petrographic and field data also bear on the locations of possible heat sources. The eruptive rocks of O'Neill and Strawberry Craters record magmatic processes that seem likely to have occurred high in the crust. Each vent consists of a cone and flow of basaltic andesite with a late silicic vitrophyre plug that barely reached the surface within the cone. At O'Neill Crater the SiO_2 contents of the initial cone, the flow that breached it, and the late plug are, respectively, 54.5, 59, and 67%. At each of the two vents, the earlier basaltic andesite spatter forms inclusions in the later vitrophyre. However, fragments of the vitrophyre are also included in the earlier erupted spatter. Hence, at each vent the basaltic andesite liquid, on its way to the surface, entrained inclusions of vitrophyre that must already have existed as a discrete melt which would subsequently form a small central plug.

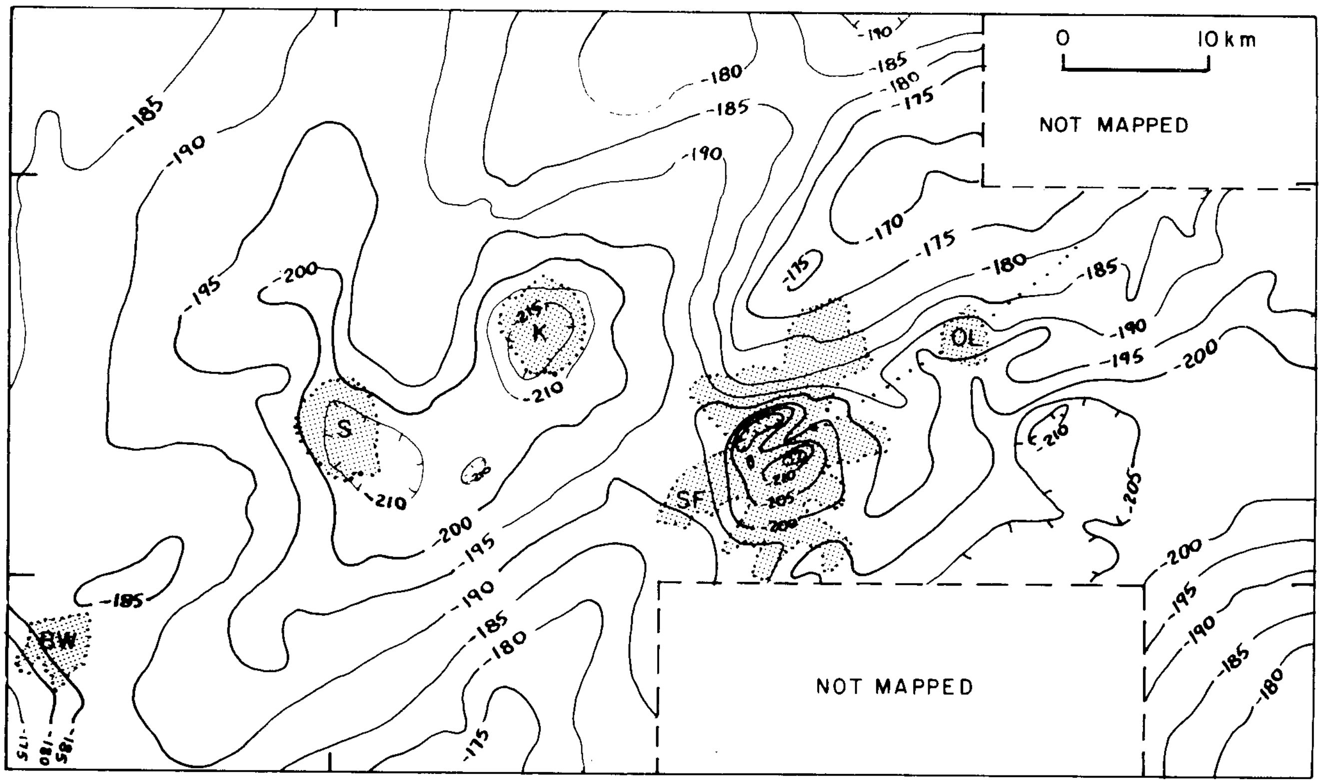

Figure 5.5.11 Preliminary Bouguer gravity map of part of the San Francisco volcanic field (J. D. Hendricks, in preparation). Contour interval 5 mgal. Light dotted lines show locations of silicic centers; BW - Bill Williams Mt.; S - Sitgreaves Mt.; K - Kendrick Peak; SF - San Francisco Mt.; OL - O'Leary Peak.

Igneous processes that could be indicative of a shallow crustal magma chamber are also recorded in the O'Leary Peak rhyodacite porphyry domes. The porphyry has a somewhat variable chemical composition and contains abundant large sanidine phenocrysts that are rimmed by oligoclase. It also contains abundant inclusions of fine-grained hornblende andesite and abundant amphibole crystals identical in composition to those of the andesite inclusions. The variable composition of the porphyry and its phenocrysts of hornblende and jacketed sanidine may record assimilation of hornblende andesite, preserved in part as inclusions, by rhyolitic magma. The fine texture of the hornblende andesite implies that it crystallized at shallow depth.

Xenoliths of igneous ultramafic and gabbroic rocks, commonly associated with granulite xenoliths, are abundant in some of the basalts and also occur, along with granulitic xenoliths, in the Strawberry Crater vitrophyre. Stoeser (1974) interpreted the igneous xenoliths as cumulus rocks representing layered intrusive bodies formed over a wide range of depths in the crust. He concluded that alkalai-olivine basalt magma, like that represented by the numerous basaltic lavas, was the probable parent magma for the intrusives, and that the granulite fragments are samples of the Precambrian country rock.

Rhyolitic ash from the Sugarloaf vent (Fig. 5.5.10), as well as many other rhyolitic ashes in the volcanic field, contains schist fragments that probably represent an upper part of the crystalline Precambrian basement. These fragments, possibly entrained where the rhyolitic magma vesiculated violently, imply that magma chambers associated with rhyolite production must be within the crystalline Precambrian basement (approximately 1 to 2 km).

Core Ridge-O'Leary Peak Vent Alignment. The San Francisco Mountain stratovolcano has been largely transected by an east-northeast-trending, graben-like, linear depression, the Interior Valley. At its southwestern end is the Core Ridge, which has a strong linear topographic element parallel to the Interior Valley and may be an exposed portion of the conduit system that fed the volcano. Directly in the mouth of the Interior Valley is the Sugarloaf rhyolite dome, and approximately on the same east-northeast trend are O'Leary Peak and Strawberry Crater. The Interior Valley formed after construction of the stratovolcano and before the eruption of the Sugarloaf rhyolite--hence between 400,000 and 200,000 yr ago. Coincidence of the line of youthful vents with the linear trend of the similarly youthful Interior Valley suggests that they formed under the influence of a common structural control, and the relatively narrow age span suggests further that the magmas may be closely related in genesis. The group of aligned vents coincides closely with an aeromagnetic low that is strongly linear and about 2 km wide (Fig. 5.5.12), and which coincides in part with a moderate gravity low (Fig. 5.5.11).

HDR. Geologic evidence and the limited geophysical data suggest two general areas that seem particularly likely areal sites to be underlain by a pluton or magma chamber. In order of preference, they are the area of the Core Ridge-O'Leary vent alignment and the Sitgreaves Mountain-Kendrick Peak area.

The area of the Core Ridge-O'Leary Peak vent alignment should be the first priority target for HDR. The youngest rhyolitic rocks in the volcanic field occur in this group of vents, which is roughly centered among the youngest known basaltic vents (Fig. 5.5.10). Field relationships, xenoliths, and petrologic data support the hypothesis that a magma chamber or chambers existed within the crystalline Precambrian basement. The linear magnetic low (Fig. 5.5.12) coincident with the aligned vents may record the presence in the subsurface of rocks characterized by either low magnetic susceptibility, high temperature, or both. Gravity data (Fig. 5.5.11) are less compelling, but the weak low coincident in part with the aligned vents may record the presence of low-density silicic rock within the crust.

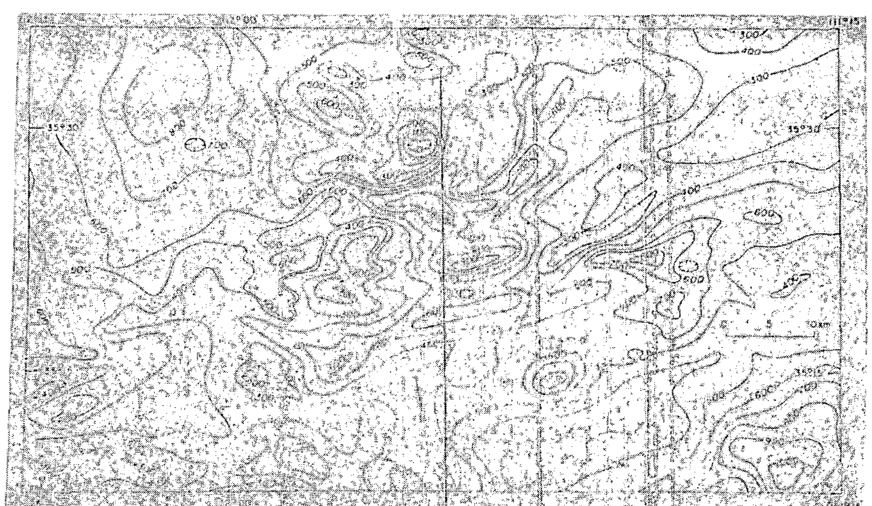

Figure 5.5.12 Aeromagnetic map of the San Francisco Peaks.

In the Sitgreaves-Kendrick area the strong gravity low (Fig. 5.5.11) is indicative of a body of low-density rock in the crust. Coincidence of the low with the belt of rhyolitic domes suggests that the body could be a silicic pluton. Xenoliths in rhyolitic ash units indicate that the rhyolites were generated at a level no higher than the upper part of the crystalline basement; depth to a pluton is probably greater than 1 to 2 km. Most of the silicic extrusives are older than 2 m.y., but the occurrence of several units between 1 and 2 m.y. old in the Kendrick Peak area suggests that the northeast end of the belt may contain HDR resources. However, because of its greater age, this belt is not as likely a source of HDR as the Sugarloaf-Strawberry area.

Additional Research Needs. In order to define possible HDR, additional geologic mapping and related petrologic studies, focused directly on the magmatic and tectonic history and processes are needed. Gravity and aeromagnetic data exist. Other techniques, especially seismic refraction, microearthquake surveys, and magnetotelluric soundings would provide data on crustal structure and the possible existence of hot or molten rock. Heat flow surveys of the most promising areas could then be planned.

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5.5.C Mt. Shasta, CA

Introduction. Andesitic stratovolcanoes of the volcanic arcs should be considered among the types of igneous systems that have potential significance for geothermal resources. There are three such major arc-type systems in the U.S., the aleutian arc, the Wrangell volcanic region of Alaska, and the Cascade Range of Washington, Oregon, and California. (The only geothermal system in the Soviet Union that has been used to generate power is in Kamchatka, a volcanic arc of this type.) Any major program designed to characterize the HDR resource in the U.S. should at some point be aimed toward one of the more promising volcanic systems in at least one of these arcs.

At present the choice of a specific area as a good target for locating and characterizing an HDR system in one of these arcs must include some more-or-less arbitrary factors that are not strictly technical; principally, the choice has been made within the Cascades rather than Alaska because of the greater accessibility, proximity to energy markets, and generally better geologic knowledge of the Cascade volcanoes. The specific reasons for considering Mt. Shasta as the primary target are summarized below, but other suitable candidate sites exist in the Cascades if studies at Mt. Shasta should prove infeasible for nontechnical reasons.

Geologic and Geophysical Setting. Mt. Shasta, in northern California, lies near the southern end of the Cascade volcanic chain (Figs. 5.5.13 and 5.5.14). Of the major Cascade volcanoes only Lassen Peak lies farther to the south, and it is offset from the continuous linear belt in which the other major volcanoes of the chain lie. Mt. Shasta is at the end of this continuous belt and is immediately adjacent to the mountainous terrane of pre-Tertiary plutonic and low-grade metamorphic rocks of the Klamath region, south and west of the volcano. A few exposures of these pre-Tertiary rocks also are present just north of Mt. Shasta, but to the east toward the Medicine Lake Highland and far beyond the only bedrock is late Cenozoic volcanic rocks. A sharp gravity gradient (Fig. 5.5.15) marks the overlap from the Klamath region to Mt. Shasta and its bordering volcanic terrane (LaFehr, 1965; Chapman and Bishop, 1967; Kim and Blank, 1972). The volcanic terrane is marked in the Shasta region by a relative gravity low that extends well beyond Mt. Shasta itself to include the area northeast and east as far as the Medicine Lake volcano, although the

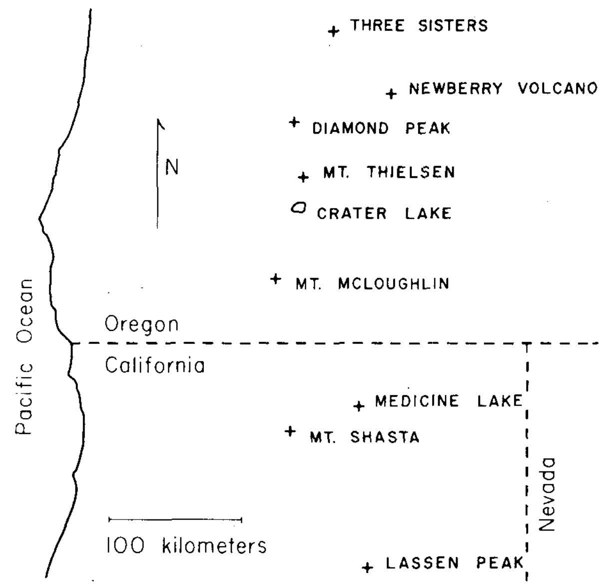


Figure 5.5.13 Map showing the location of the major stratovolcanoes of the southern Cascade range in California, Oregon, and Washington.

latter is marked by a smaller positive gravity anomaly within the larger gravity low. The significance of this large negative gravity anomaly is uncertain, but it may relate to the configuration of the plutonic-magmatic underpinning of this part of the Cascades. Whether this larger gravity feature reflects an active zone of magmatism within the crust is conjectural, but there is ample geologic evidence of very young volcanism within the zone that is marked by this gravity feature. A conspicuous positive aeromagnetic anomaly is associated with the mountain (Figs. 5.5.16 and 5.5.17).

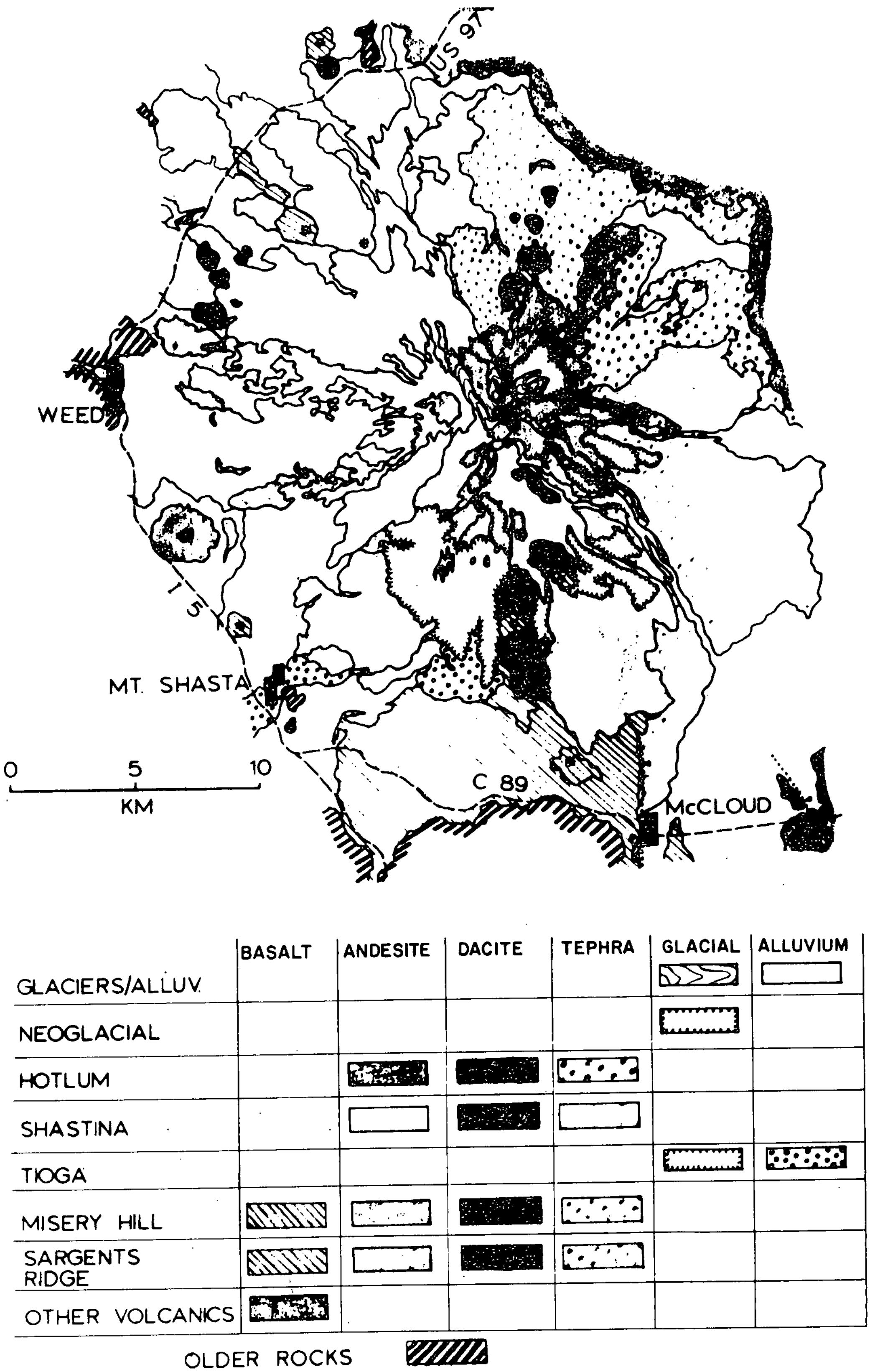


Figure 5.5.14 Geologic map of the Mt. Shasta area.

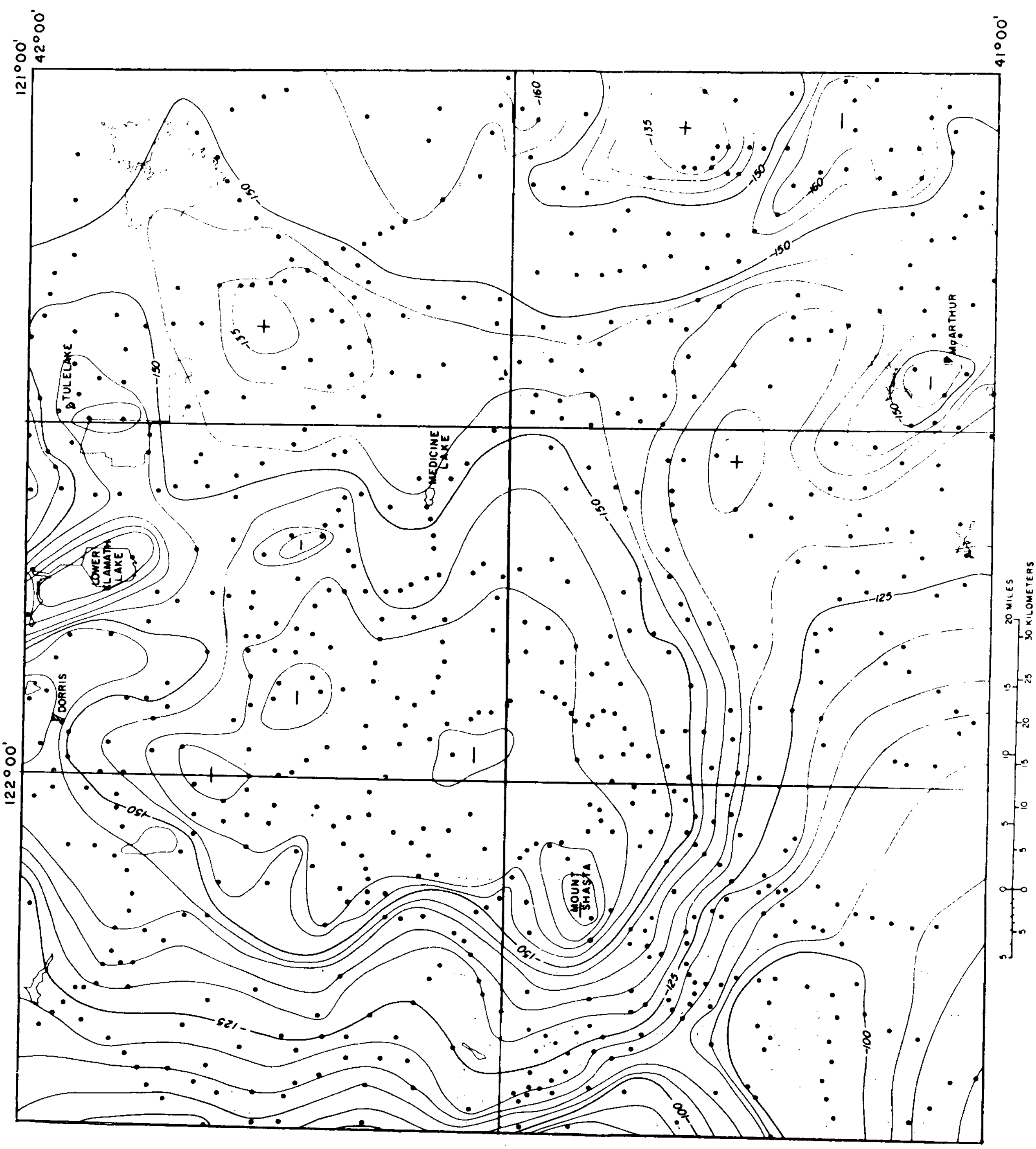
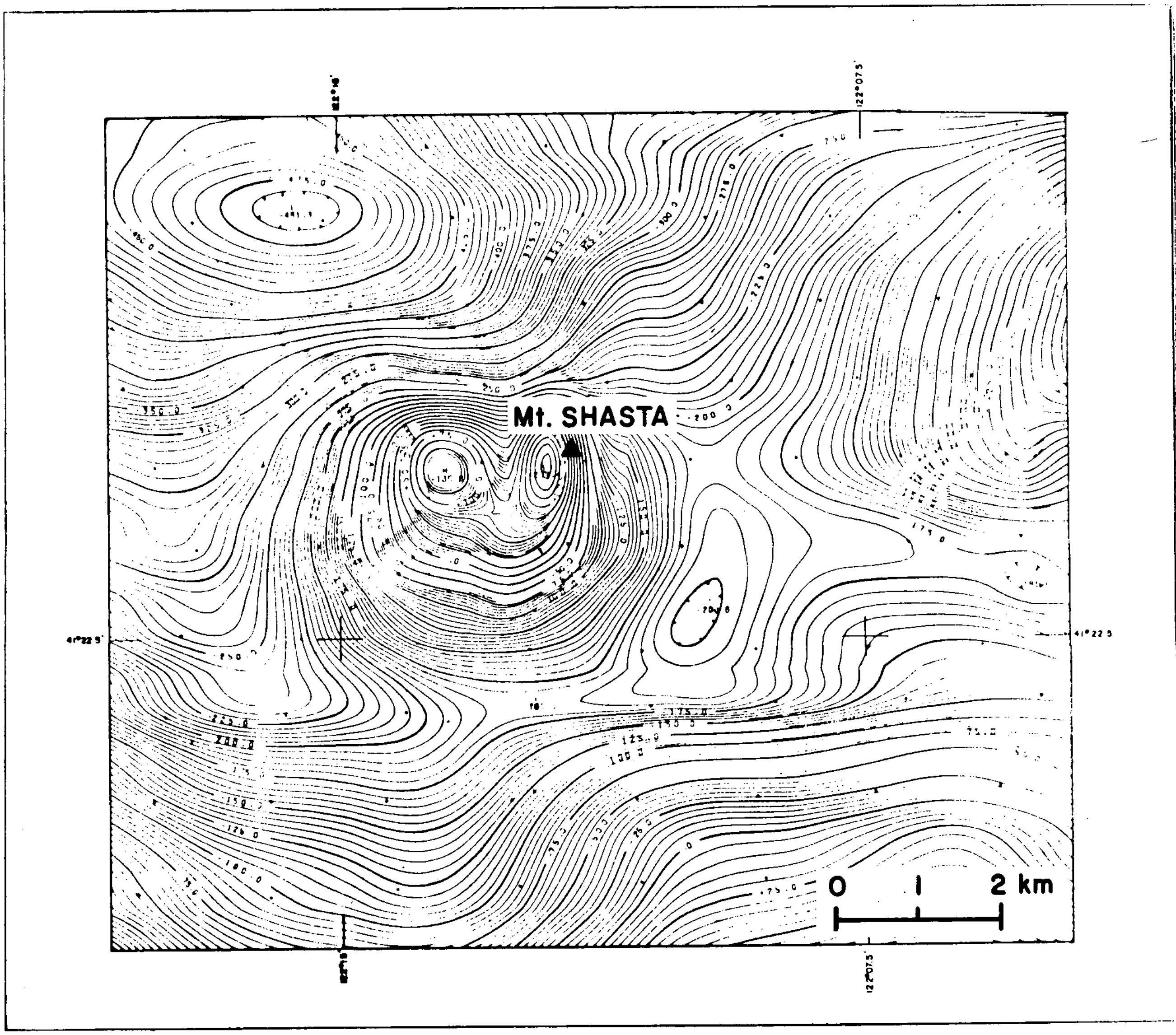


Figure 5.5.15 Gravity map of part of northern California including the Mt. Shasta area.



RESIDUAL MAGNETIC INTENSITY
Shasta, California
U.S. Geological Survey
Area "A"

AEROMAGNETIC MAP

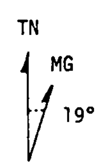
EXPLANATION

Magnetic contours showing total intensity magnetic field of the earth in gammas relative to an arbitrary datum. Hachur ticks indicate areas of lower intensity.

A regional trend of 7.72 gammas/mile north and 4.45 gammas/mile east was removed using I.G.R.F. updated to July 1975. Map shows original computer drawn contours.

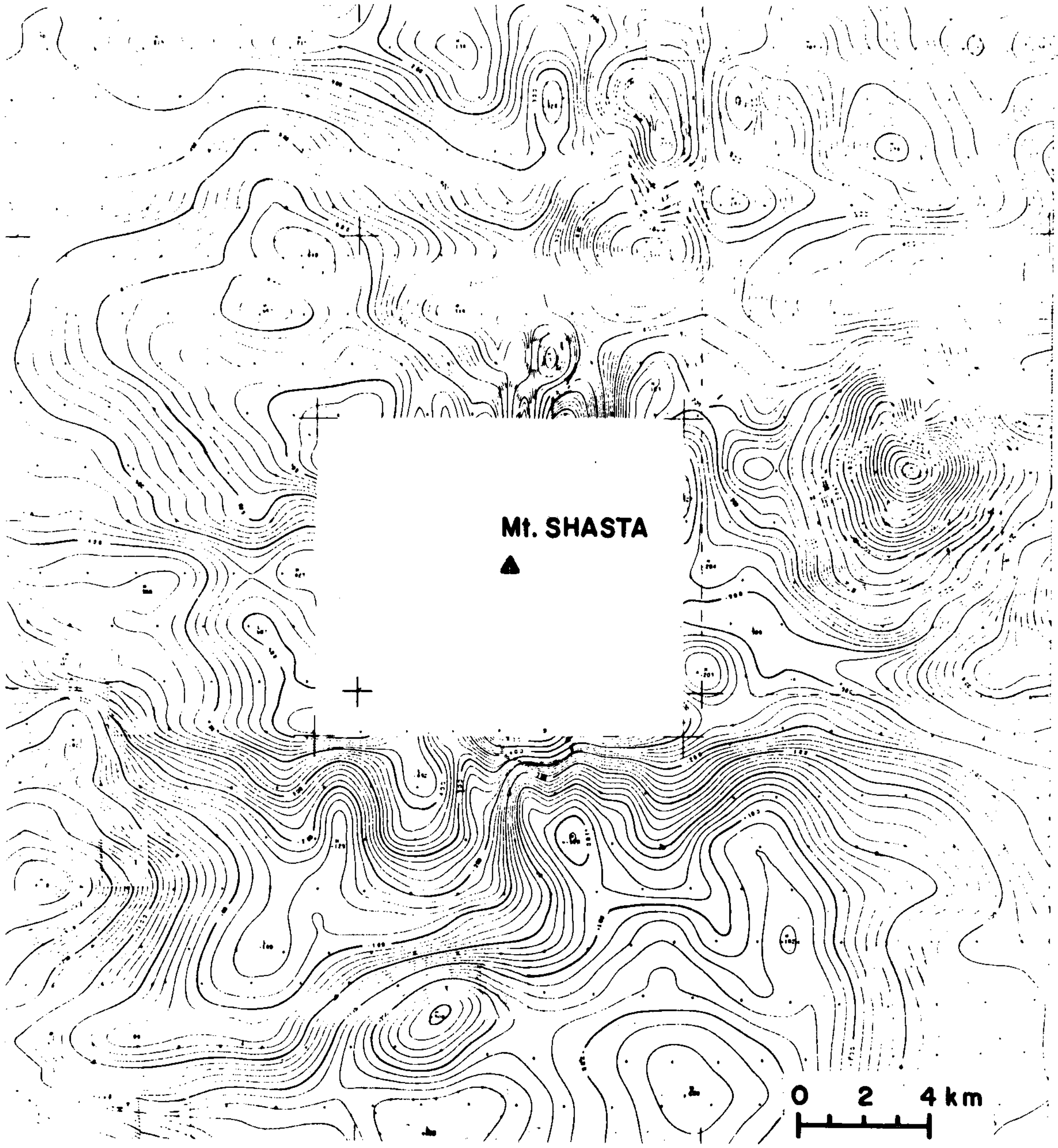
Datum base of 53,359.4 at lower left hand corner.

Contour Interval . . . . 5 gammas
Flight Line Spacing . . . . one mile
Flight Altitude . . . . 14,500'
Flown & Compiled . . . . July 1975
Aerial Surveys, S. L. C., Utah



Approx. Magnetic Declination

Figure 5.5.16 Residual magnetic intensity map of part of northern California; the Mt. Shasta area is shown in more detail in Fig. 5.5.17.



RESIDUAL MAGNETIC INTENSITY
Mt. Shasta, California
U.S. Geological Survey
Area "A"

EXPLANATION

Magnetic contours showing total intensity magnetic field of the earth in gammas relative to an arbitrary datum. Hachure ticks indicate areas of lower intensity.

A regional trend of 7.73 gammas/mile north and 4.45 gammas/mile east was removed using I.G.R.F. updated to July 1975. Map shows original computer drawn contours.

Datum base of 53,291.4 at lower left hand corner.

AEROMAGNETIC MAP

Contour Interval. . . . . 20 gammas
Flight Line Spacing . . . . . . one mile
Flight Altitude . . . . 8,500'
Flown & Compiled . . . . July 1975
Aerial Surveys, S. L. C., Utah

TN
MN
19°
Approx. Magnetic Declination

Figure 5.5.17 Residual magnetic intensity map of the Mt. Shasta area, California.

Volcanic History. Mt. Shasta itself represents a complex volcanic history, more involved than the massive volcanic one might seem to imply (Christiansen and Miller, 1976). At least four distinct episodes of cone-building volcanism are clear. Each of these episodes appears to reflect a relatively brief time (less than a few thousand years) of rapid eruption of pyroxene-andesite lavas and pyroclastic breccias followed by a somewhat more protracted period of more silicic volcanism (through hornblende andesites to dacites). Some petrochemical and isotopic data are available for these rocks (Williams, 1934; Smith and Carmichael, 1968; Peterman et al., 1970; Steinborn, 1972; Condie and Swenson, 1973; and unpublished data of R. L. Christiansen). Generally a longer period of time with more erosion than volcanism intervened between the principal cone-building episodes. This longer time, characterized by dacite domes and flows at the summit and on the flanks of each of the four pyroxene-andesite cones that constitute Mt. Shasta and accompanied or followed by sufficient time for much erosion, implies the existence of a magma chamber at a relatively high level in the earth's crust.

Williams (1932, 1934) showed that many of the more silicic domes and flows of Mt. Shasta lie along a north-trending zone of vents through the summit of the mountain and also at and below Shastina, a prominent satellitic cone on the west side of the mountain. Williams thought that these silicic vents represented a very late stage of evolution of the entire volcano, but more recent work (Christiansen and Miller, 1976) shows that the silicic domes were emplaced at various times during the later stages of each of the four main cone-building episodes.

Dating of Mt. Shasta's four main volcanic episodes is still preliminary. However, stratigraphic evidence relating them to regional glaciations and evidence from the degrees of soil development on deposits of each volcanic sequence provide a chronologic framework. In addition, radiometric dating of these units is in progress, and some results--most of them preliminary--are available. These data show that the oldest of the sequences predated the Tahoe Glaciation and, thus, is older than 100,000 yr. The second recognized sequence is younger than the Tahoe but older than the Tioga Glaciation. Its cone was largely complete sometime before 12,000 yr ago, but the last episode from this cone, a major pumice flow, is younger than a minor late-Tioga or post-Tioga glacial advance that occurred less than about 12,000 yr ago. Mt. Shasta's third cone, Shastina, overlies the post-12,000 yr pumice flow; the dacite domes and pyroclastic flows that mark Shastina's last activity (Crandell, 1973; Miller and Crandell, 1975) have been dated by ^{14}C methods as about 9,000 to 9,500 yr old. The youngest major episode of volcanism at Mt. Shasta has produced the upper cone of the mountain, its summit, and its northern and northeastern flanks. This activity was younger than the early Neoglaciation, 3,000 to 4,000 yr ago, and the dacitic summit dome (the youngest major volcanic unit) still has active fumaroles and a small acid hot spring. It is possible that an eruption of Mt. Shasta was observed from the Pacific Ocean in 1786 (Finch, 1930).

Geothermal Potential. The dacitic domes at the summit of each of the four recognized cones that form Mt. Shasta and along the flanks of most of them probably indicate the existence of shallow crustal magma chambers that existed late during the evolution of each cone. Three of these chambers held magma during the last 12,000 yr, and the youngest has probably produced a major eruption within the last 1,000 yr. The youngest chamber probably is still active; it and the somewhat older cooling plutons, all in the midst of the recurrently active area of andesitic volcanism, are likely to maintain a significant crustal thermal anomaly. Digital modeling of the aeromagnetic survey data (R. J. Blakely, written commun., 1976) supports the existence and probable shallow depth of a hot subsurface body beneath the main peak of Mt. Shasta.

No drill hole data exist for Mt. Shasta, and only very limited hydrological information is available. The drainages from the mountain are mostly intermittent. Most of the precipitation on the mountain infiltrates its porous carapace and emerges in large cold springs along its western flank, draining into the Sacramento River system and a tributary of the Klamath River system. This suggests that any target for HDR exploration should be within the basement that lies beneath and adjacent to Mt. Shasta and is known from exposures on its southern, western, and northern flanks. The first effort of any such exploration program should go into geophysical work designed to characterize this basement, to estimate its configuration in the vicinity of the volcano, and to define any magma chambers or hot plutonic bodies and their aureoles in the crust around and beneath the volcano.

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5.5.D Medicine Lake Highland, CA

Introduction. The Medicine Lake Highland (Powers, 1932; Anderson, 1941) is one of three large shield volcanoes that lie along the east side of the High Cascades (Fig. 5.5.13) and belong to the basalt-rhyolite lava suite. The two other members of the group are the Newberry Volcano in Oregon (Fig. 5.5.13), an almost identical twin of Medicine Lake, and the Simcoe Mountains in Washington. Volcanic activity at the Highland is characterized by frequent small- to moderate-volume ($\sim 1\ km^3$) eruptions, with pyroclastic debris subordinant to lava flows. Vents are widely distributed and, with the possible exception of the early shield building stage, apparently short-lived. The Highland is about 45 km in diameter and rises 1200 m above its base. The estimated total volume of the volcanic pile, exclusive of underlying Modoc Plateau (Warner) basalt, is $10^3 km^3$. Paleomagnetic studies on representative volcanic units suggest that the entire pile developed in the last 700,000 yr. This implies a minimum (since erosion is neglected) lava output of $1.4 \times 10^{-3}\ km^3/yr$, a rate that has been exceeded during the last 1000 yr.

Evolution of the Highland. Interpretation of the volcanic and tectonic history of the Highland is hampered by a lack of dissection by erosion. Early Highland lavas are almost completely mantled by late Pleistocene to Recent flows. Similarly, although there is pervasive evidence of a long period of Basin and Range-type normal faulting to the north, east, and south, only small Recent scarps can be found on the Highland. Most of these are directly related to the caldera or Recent vents.

The dominant and earliest structure of Quaternary volcanism was a broad shield volcano (Fig. 5.5.18) of basalt and andesite lava flows and tuff; but even early in its evolution, rhyolite and dacite flows were present. Before the end of glaciation, the summit of the shield volcano collapsed by about 150 m to form an ellipsoidal caldera 8 by 6 km. Then viscous andesite (olivine-free, unlike most shield lava) erupted along the caldera rim to form a rampart of small steep cones. After glaciation, numerous rhyolite flows, dacite flows, and the Glass Mountain rhyolite and dacite flow erupted at high elevations inside and outside the caldera. Fresh cinder cones and associated floods of basalt and andesite, one of which, Burnt Lava Flow, is as young as Glass Mountain, mantle the flanks of the Medicine Lake Highland. Anderson

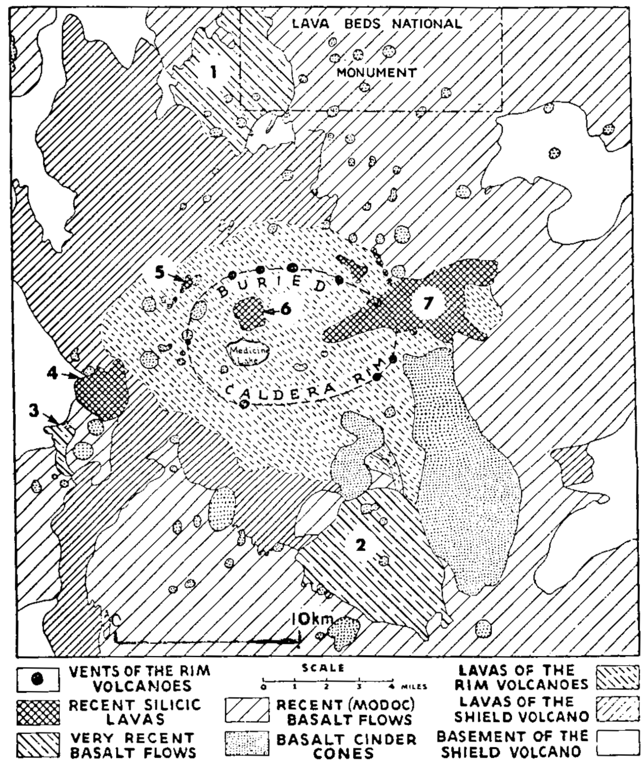

Figure 5.5.18 Generalized geologic map of the Medicine Lake Highland (Anderson, 1941). Numbers refer to youngest volcanic features (<<10^4 yr) as follows:

1. Callahan flow and cone - andesite
2. Burnt Lava flow and High Hole Crater (cinder basaltic andesite
3. Paint Pot Crater flow - Basalt
4. Little Glass Mountain flow and pumice - rhyolite
5. Grouse Hill domes and pumice - rhyolite
6. Medicine Lake flow - dacite
7. Glass Mountain flows, domes and pumice - rhyolite to dacite

(1933) explained the scarcity of vents on the caldera floor as an indication that the floor was not highly fractured during collapse. Although silicic magmas have found their way up the caldera ring fracture, it is unlikely that a large body of silicic magma occupies the area under the caldera because uncontaminated olivine basalt has also erupted in the immediate vicinity of the caldera during the post-collapse period.

The youngest volcanic features are shown in Fig. 5.5.18. Features 2, 4, 5, and 7 are probably 200 to 500 yr old. Evidence of major surface deformation is associated with the young rhyolite domes (4, 5, and 7) in the form of radiating open fissures. The largest of these features and the only one with a known thermal anomaly is the Glass Mountain complex (7) on the east side of the caldera (Finch, 1928; Anderson, 1933; Chesterman, 1955; Friedman, 1968; and Eichelberger, 1975). The present period of activity began toward the end of glaciation with the extrusion of the rhyolite flows, domes, and pumice of Mt. Hoffman. This was followed, perhaps 2000 yr B. P., by the Hoffman rhyolite and dacite flow, two massive rhyolite pumice eruptions at about 1000 yr B. P., and the Glass Mountain rhyolite and dacite flow and rhyolite domes within the last few hundred years. The last rhyolite to be erupted lacks phenocrysts, indicating that the magma is at or above its liquidus temperature. Substantial assimilation of basaltic shield lavas by the magma produced the dacite of this complex. The associated thermal area, the Hot Spot, is an acre of barren pumice with temperatures of 80°C at 0.5-m depth. At present there is one quiet steam vent. The hottest region is elongate and is parallel to and midway between the fissures that vented the Hoffman and Glass Mountain flows.

Possible HDR. The long history of silicic volcanism at the Highland implies high temperatures at shallow levels, especially in the vicinity of Glass Mountain. However, the nearly complete absence of steam suggests that the volcanic pile is rather dry. This is probably due to the height of the pile above surrounding topography and its high permeability. Since there is ample surface water at the level of the base of the shield, hydrothermal systems might be present within the shield at depth's greater than 1 km. Two possibilities for HDR exist:

(1) The crystallized part of a batholith, comagmatic and contemporaneous with the present extrusive activity. The existence of such a batholith under Shasta and the Highland has been suggested by Heiken (1976) on the

basis of LaFehr's (1965) gravity data and a circular topographic depression encompassing this region.

(2) Heated crystalline rocks of the underlying Sierra Nevada- or Klamath Mountains-type plutonic basement. Evidence that such rocks may exist at depth is the occurrence of gabbroic xenoliths in some Highland (A. T. Anderson, 1975) and Shasta lavas.

Evaluation of these possibilities depends on additional geophysical investigation and heat flow surveys because the crystalline rocks are nowhere exposed.

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5.6 Coexisting HDR and Hydrothermal Systems

For practical reasons, HDR associated with known or producing hydrothermal systems may be especially important. At these localities, the experimental aspects of HDR energy extraction technology as well as HDR resource assessment can go in parallel with hydrothermal development. A single geological model will contribute to resource assessment of geothermal energy stored as HDR, hydrothermal, and magmatic heat. This report has not emphasized the HDR associated with hydrothermal systems, because it may be a relatively small part of the HDR resource base. However, in terms of economically recoverable HDR, that is, geothermal resources, these may be very significant. The HDR resource base associated with hydrothermal systems might be considered specifically in a future HDRAP report. In particular the HDR associated with the known or producing hydrothermal systems at the Geysers; the three Imperial Valley, California, fields; and Roosevelt Hot Springs, Utah, should be reviewed. "Dry holes" have been drilled in all of these locations. The coexistence of HDR and hydrothermal systems at Fenton Hill, is already demonstrated; at Coso and Long Valley it is likely.

It is noteworthy that marginally productive or unproductive geothermal wells drilled within or at the peripheries of hydrothermal fields are, in fact, already the target of two ERDA efforts: the ERDA-DGE stimulation program, for which a PRDA has been issued and industrial response received; and Project 1 of the U.S. - Italy agreement for cooperative RD&D on geothermal energy, now being implemented by ERDA and ENEL (Ente Nazionale per l'Energia Electrica, the Italian National Electrical Agency).

Table 5.6.I shows the exploration and development status of existing geothermal systems. In general, both types of geothermal heat coexist in most geothermal systems.

Table 5.6.I A summary of coexisting HDR and geothermal systems.

		Site	Description of Geology	Remarks on the Types and Location of Various Possible Geothermal Heat Sources: HDR	HYDROTHERMAL	MAGMA	Status of Exploration and Development: HDR	HYDRO
HOT DRY ROCK SITES	Drilled or being drilled for exploration or development	Marysville, Montana	A Tertiary pluton in northern Rockies.	Drilling revealed deep hydrothermal circulation in granite stock.	Deep hydrothermal system is demonstrated. Utility probably marginal.	Probably none, unless at great depth.	2	2
HOT DRY ROCK SITES	Drilled or being drilled for exploration or development	Fenton Hill (Valles) New Mexico*	A young and large silicic caldera complex, developed in Precambrian granite basement.	HDR in Precambrian granites surrounding the caldera; deep drilling and demo in progress by LASL.	Resources being developed by Union Oil within the caldera.	Probable magma chamber at depth of 4 to 6 km; still partially molten.	3	4
HOT DRY ROCK SITES	Drilled or being drilled for exploration or development	Coso, California**	A large ring fracture system with young dome cluster in the center; developed in Mesozoic granite basement.	HDR may exist several places at depth in structure.	Possible hydrothermal system in center of structure near or in domefield.	Youth of domefield volcanism implies magma at depth.	2	2
HOT DRY ROCK SITES	Sites recommended by HDRAP for exploration and possible development	Long Valley, California**	Large resurgent caldera complex with tuff and ring-fault volcanism, similar to Valles, only larger.	Probably extensive in west part of caldera & in area between Long Valley & Mono Craters.	Believed to be significant within the caldera. Exploration and drilling in progress.	Youth of volcanism together with large size implies magma at depth; evidence for renewal also abundant.	2	2
HOT DRY ROCK SITES	Sites recommended by HDRAP for exploration and possible development	San Francisco Peaks, Arizona	A linear array of silicic domes in a field of young predominantly mafic volcanoes.	Associated with young silicic plugs at depth, if present.	Unevaluated.	Unknown; probably none near surface.	1	0
HOT DRY ROCK SITES	Sites recommended by HDRAP for exploration and possible development	Shasta, California	An active stratovolcano producing principally andesite rocks and tephra with isolated dacite domes. Basement low-rank metamorphic rocks.	Heat stored in the basement rocks underlying volcanoes transferred from dacite magma chambers.	Could exist within the volcanic pile.	Young dacite domes and flows indicated likely shallow magma.	1	0
HOT DRY ROCK SITES	Sites recommended by HDRAP for exploration and possible development	Medicine Lake Highland, California	Dacite to rhyolite domes and flows of very young age erupted from atop a broad shield of older andesitic rocks.	Heat could be stored in plutonic basement rocks, transferred by young magma bodies; unexplored.	Could exist within the volcanic pile; hot springs present.	Young volcanics implies magma at depth.	1	1
HYDROTHERMAL SITES		Geysers, California**	Natural hydrothermal system in highly fractured, low rank metamorphic and Mesozoic igneous rocks.	Possible in unproductive, deep, dry holes.	Shallow reservoir believed to be fed by fractures.	Probably deep.	2	5
HYDROTHERMAL SITES	Imperial Valley, California	Salton Sea (Niland)**	At various locations within the Salton trough, a large fault bounded basin or graben; heat source may be magma intruded to shallow depth.	Possible HDR in basement rocks at depth, or in low-permeability sediments at shallow depth.	Temperatures to 360°C in dense brines at 2.4 km depth.		2	4
HYDROTHERMAL SITES	Imperial Valley, California	East Mesa (Holtville)**			No surface discharge; estimated subsurface temperature of 180°C degrees.	Possible shallow magma at several localities.	2	4
HYDROTHERMAL SITES	Imperial Valley, California	Heber**			Similar to East Mesa.		2	4
HYDROTHERMAL SITES		Puna District, Hawaii	East rift zone of Kilauea volcano, Hawaii. This is one site of many basalt flank eruptions during historic times.	Possible but very unlikely because of pervasive hydrothermal action in the volcanic pile.	Drilling by University of Hawaii consortium has demonstrated hot (350°C) water at 1950 m. Hydrothermal development may be feasible.	Unlikely since magma is erupted onto surface as flows. (Lava lakes elsewhere on this rift zone could be a magma source).	2	2
HYDROTHERMAL SITES		Roosevelt Hot Springs, Utah**	A fault zone along the west side of the Mineral Mountains within the Basin Range Province.	Possible development of existing dry holes.	Secondary recovery techniques.	None.	2	3

Footnotes

*Sites currently under investigation/development for both HDR and hydrothermal systems.

**Sites with definite potential for both HDR and hydrothermal resources.

KEY

Exploration/Development

0 = not explored
1 = exploration by surface methods
2 = drilled or in progress
3 = demonstration in progress
4 = development in progress
5 = producing

5.7 Conduction-Dominated, Non-Igneous HDR

Diment et al. (1975) have shown that the conterminous U.S. can be divided into three broad regions in terms of thermal structure of the crust, called Basin-Range type, Eastern type, and Sierra Nevada type (see Fig. 5.7.1 and Table 5.7.I). Much of the west, constituting about 25% of the surface area of the conterminous U.S., has high heat flow with probable temperatures at 10 km near 290°C. Most of the eastern U.S. has moderate heat flow with temperatures at 10 km of about 170°C, constituting about 73% of the country. A low heat flow province with temperatures of 120°C at 10 km underlies the Sierra Nevada in California.

Table 5.7.I Properties of four crustal thermal structure models.

	HDR Category 1	HDR Category 2		
	Igneous Related	Basin-Range Type	Eastern Type	Sierra Nevada Type
% Total Surface Area	0.093	23.0	75.3	0.87
A (HGU)		5	5	5
g* (HFU)		1.4	0.8	0.4
D (km)		10	7.5	10
T°C at 3 km	200	90	55	40
6 km	400	180	110	80
10 km	667	290	170	120

A, radioactive heat generation rate. Units (HGU), 10^{-13} cal/cm^3 sec.

g*, so-called reduced heat flow, which is the contribution of conducted heat from the earth's interior below a depth D. Very roughly it is approximately the conducted heat flux from the earth's mantle and is thought to be nearly uniform within heat flow provinces. Units (HFU) are 10^{-6} cal/cm^2 sec.

D, Thickness of layer that contains radioactive sources given by A above.

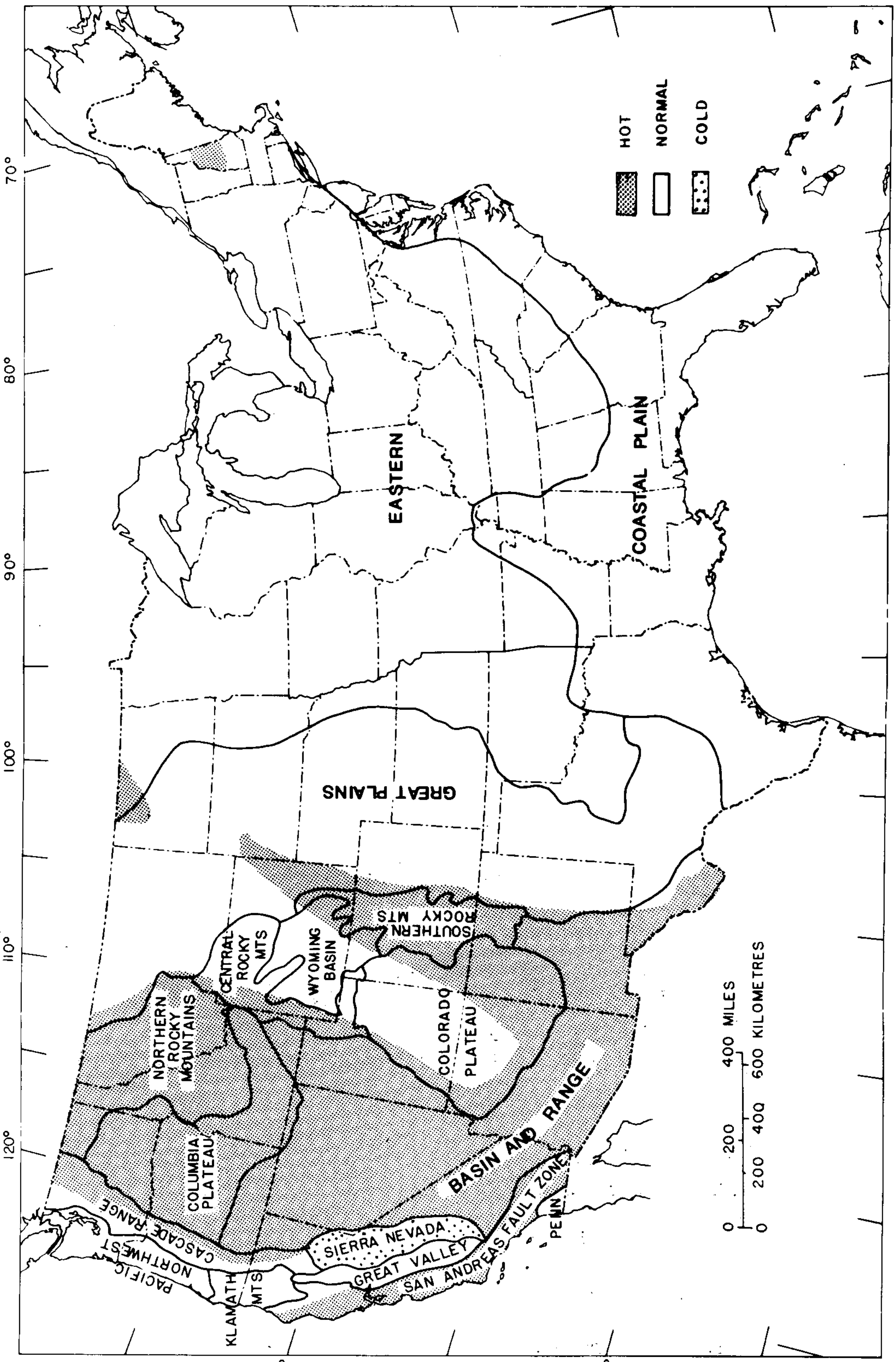

Figure 5.7.1 Map showing the distribution of principal crustal heat flow provinces within the conterminous United States (after Diment et al. (1975) (a) Western U.S., (b) Eastern U.S.

Temperature as a function of depth in these three types of crustal models is shown in Fig. 5.7.2. These models are only average values, and substantial variations exist within each province depending on many factors, such as local variations in thermal conductivities, sediment thickness, radioactive heat generation, and tectonic setting. In discussing the potential for HDR in the western third of the U.S., Brown (1973), using data largely from Roy et al. (1972), showed substantial areas may be significantly above the average temperature. For example, the typical Basin-Range thermal gradient implies a temperature of about 180°C at 6-km depth; however, 7% of the area may have temperatures greater than 330°C at that depth, 17% greater than 285°C. Furthermore, there is considerable doubt about the thermal state of the deeper regions of these hotter parts of the crust. Brown (1973) argues for a median temperature at 6 km of 233°C for the western U.S., rather than the 180°C of Diment et al. (1975). Of particular interest are local variations or anomalies within each province that might be usefully exploited, such as in the vicinity of known hot springs that may be fault controlled, as in the Basin-Range Province.

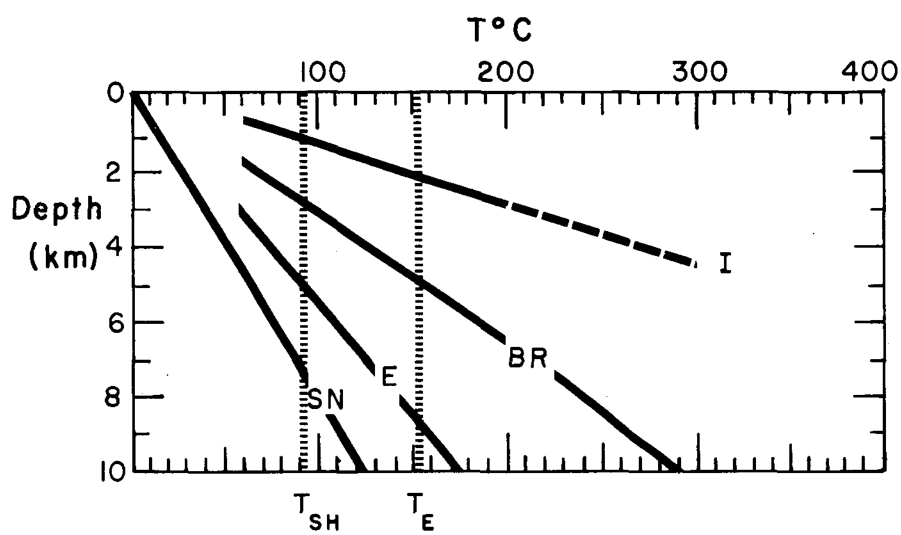

Figure 5.7.2 Temperature as a function of depth in each of the four major types of thermal structure. SN is Sierra Nevada type; E, the Eastern type; and BR, Basin-Range type. I is an average value assumed to be representative of HDR in igneous-related areas and corresponds to the observed heat flux in the deep HDR drill holes near the Valles Caldera, NM.

The potential thermal resources stored in the conduction-dominated part of the crust clearly are not as concentrated as are the igneous-related sites, although the magnitude of the resource base is enormous, as shown in the next section. Precise characterization of this more diffuse resource will require deep drilling, both on a regional scale and more locally where important thermal anomalies may exist. This problem has been discussed in the context of the proposed Continental Drilling Program (Shoemaker, 1975, p. 22-23).

5.8 Magnitude of the HDR Resource Base

The estimated thermal resource base of the crust within the U.S. at depths shallower than 10 km are vast. Diment et al. (1975) estimate the total heat stored in regional conductive environments to be 800×10^{22} cal (or about 32,000 Q). Smith and Shaw (1975) estimate the total heat stored in magma-related systems within the conterminous U.S. to be 2.3×10^{22} cal (about 100 Q), and about 30 times the estimated heat content of all hydrothermal systems.

However, only a fraction of this heat can be considered to be even theoretically economically extractable. To estimate the potentially usable part of the resource base, we have computed the part of the base at temperatures of 150°C or more, at depths shallower than 10 km for heat stored as igneous-related and conduction-dominated resources. In making those estimates we may use Fig. 5.7.2 which shows temperature as a function of depth for the four principal types of continental crust (Fig. 5.7.1). Basin-Range, Eastern, and Sierra Nevada types of crustal thermal structure were taken from Diment et al. (1975) with their estimates of surface area underlain by each. To compute the igneous-related HDR resource base, we assume an average thermal gradient similar to that observed in the deep drill hole at Fenton Hill (GT-2), being fully aware that the specific thermal structure within various igneous-related geothermal systems will vary, and it will vary with both space and time within any given system. The Fenton Hill gradient, in fact, is conservative, and in many places higher gradients are anticipated. Next we note that Smith and Shaw's (1975) tables show the total area of magma-related systems within the conterminous U.S. is about 8.7×10^3 km^2, or 0.093% of the total surface area.

Using the thermal gradients shown in Fig. 5.7.2 and the surface areas appropriate for each, we calculated the thermal energy within the crust, and at depths shallower than 10 km to estimate the total HDR resource base. The results, shown in Table 5.8.I, indicate that the total HDR resource base is on the order of 23,000 Q, within the conterminous U.S. The HDR exceeding 150°C is approximately 10,000 Q, most of which is in the deeper parts of the crust between 6- and 10-km depth. Furthermore, at depths shallower than 6 km, the HDR resource base above 150°C is restricted to igneous-related systems and Basin-Range-type crust.

Table 5.8.I Estimates of the HDR resource base.

	HDR Resource Base d < 10 km T > 15°C		Fraction of the HDR Resource Base (4)			% of Surface
	USGS Circular 726	This Report	d<10 km T>150°C	d<6 km T>150°C	d<3 km T>150°C	
Igneous Related	105 (2)	77 (3)	74	24	3.5	0.093
Basin-Range Type	8,230	8,305	6,302	987	0	23.8
Eastern Type	15,446	14,803	3,573	0	0	75.3
Sierra Nevada Type	130	120	0	0	0	0.87
Total	23,911	23,305	9,949	1,011	3.5	

(1) Units of Q are: $Q = 10^{18}$ BTU $= 10^{21}$ J $= 0.24 \times 10^{21}$ cal. Approximate U.S. consumption for 1972 was 0.07Q.

(2) Total based on summing individual igneous systems, including Hawaii and Alaska. Contains both molten (55Q) and crystallized (50Q) parts.

(3) Total based on simple integration using the average-igneous geotherm from Figure 5.7.2, hence should be treated as close-order-of-magnitude (±50%) estimate. Does not include latent heat of magma.

(4) Heat contents were calculated assuming all the rock at depths shallower than the indicated depths (10, 6 and 3 km respectively) and in excess of 150°C is reduced to 15°C from its initial temperature. Rock initially at temperatures below 150°C is <u>not</u> included. The heat capacity assumed was 2.71×10^{-6} Q/km³°C, equivalent to approximately 0.65 cal°C/cc. Note, that dry granite at low temperature has a specific heat of about 0.52 cal°C/cc, and basalt about 0.60; the crust is intermediate in composition and warm at moderate depth, hence the value of 0.65 is probably correct to about ± 10%.

These results are shown in graphical form in Fig. 5.8.1. Note, especially, that the total HDR resource base, and that part at temperatures above 150°C, are vastly greater than present (1972) and projected (2000) total U.S. energy consumption, although utilization of this potential resource is now at the limit of existing technology. Furthermore, the thermal energy stored in the conduction-dominated parts of the crust (Basin-Range type and Eastern type) is dispersed. Finally, at depths shallower than about 6 km, the bulk of the HDR resource is stored in igneous-related systems; at depths of 6 km and greater it is mainly dispersed in hot rocks of the conduction-dominated parts of the crust. There are about 24 Q within igneous-related systems at depths shallower than 6 km, at temperatures greater than 150°C and 3 to 4 Q at depth less than 3 km. This heat must be considered, at present, to be the high-grade deposits of HDR.

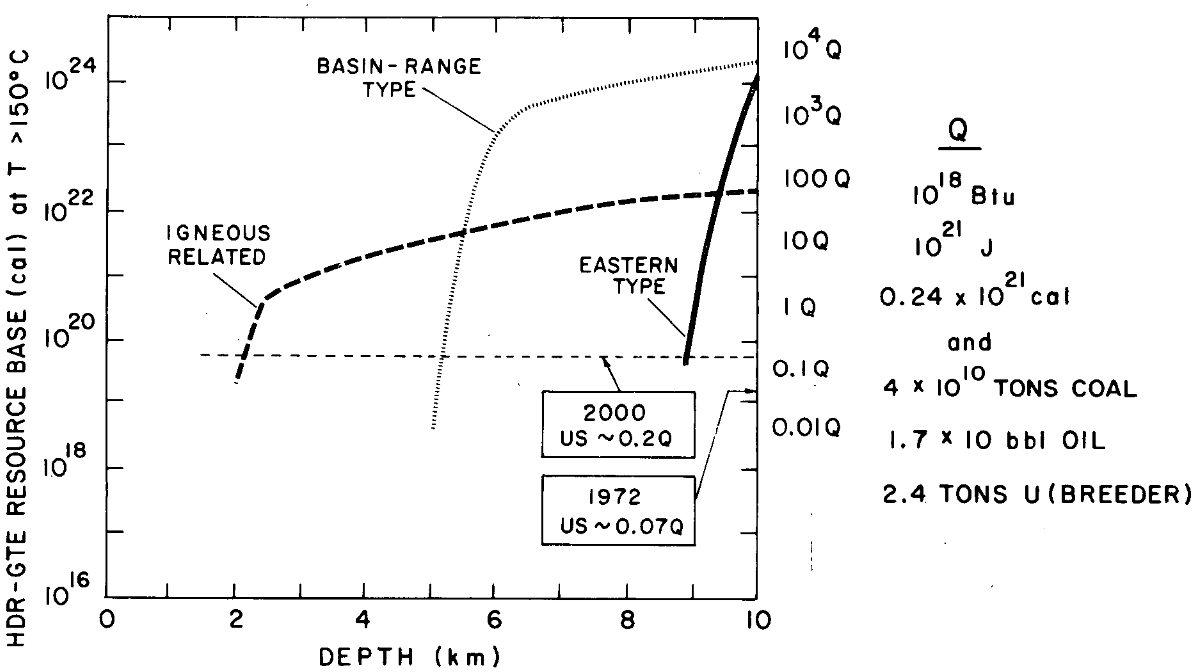

Figure 5.8.1 A representation of the estimated HDR geothermal energy resource base, at temperatures exceeding 150°C, shown as a function of depth. The boxes and arrows indicate total energy consumption of the U.S. for 1972 and projected for the year 2000.

The above discussion has focused on the potential HDR geothermal energy resources stored at 150°C or greater, the approximate lower threshold for electric power generation. Clearly, resources for other potential uses such as space heating, which might utilize 90°C temperatures, are much larger. The use of such average, generalized resource base estimates will be necessary until sufficient effort has been directed toward the detailed evaluation of the HDR resource base in several specific regional sites.

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6. RECOMMENDATIONS

The HDR site summaries and technical discussions in this report indicate that the national effort to assess HDR geothermal resources is in only its initial stages. The very preliminary and provisional nature of these estimates presented demonstrate that additional research and development effort is needed to

- o Define and categorize better HDR occurrences as to types and subtypes.
- o Develop agressively our geological knowledge of specific HDR areas to calibrate the field techniques required for resource base assessment and characterization.
- o Use the results of these detailed field investigations and the geological models developed for these specific sites to establish quantitative estimates of the magnitude of the HDR resource base.

A primary need identified in the report is for a program that provides for a systematic and thorough resource base assessment of a suite of six to eight HDR sites, carefully selected to represent the various major types of heat sources. This program should include the gathering of substantial amounts of subsurface data from intermediate depths by drilling at each site.

We recommend that the following steps and activities be taken or supported to insure that a balanced and effective program of HDR resource base assessment be maintained

(1) Stress the need for the construction of quantitative geological models throughout all phases of the HDR assessment process. Recognize that the models must be updated as new data and results become available. Consider that, indeed, results of any given phase may alter the original assessment plan as new information becomes available and indicates that initial concepts were based upon partial knowledge and that alternative interpretations are suggested.

(2) Recognize that development of quantitative geological models of representative HDR sites required to accomplish the assessment task also can be used in needed evaluations of HDR extraction technologies.

(3) Recognize that the thorough regional and local evaluation of HDR associated with a geothermal system may take 2 to 3 yr, perhaps longer if field seasons are limited by weather.

(4) Insure that future HDR resource base assessment projects cover a sufficient regional and areal extent to define adequately and characterize in quantitative fashion, the heat sources of the geothermal system. Insure, in addition, that support of the projects is sufficient to include these broad objectives. Also, insure that attention be given to the identification and characterization of associated hydrothermal resources within the geothermal systems under investigation.

(5) Provide sufficient support for future exploration and assessment projects to insure that all appropriate measurement techniques are used, and furthermore, to encourage overlap and redundancy in these investigations. This will help insure that various methods are evaluated relative to their impact on interpretations and their contributions to the final resource base characterization models.

(6) Establish a center to accumulate HDR resource base data, catalog maps, reports, references, and cores from HDR site evaluations and characterizations. Encourage use of this information base by issuing abstracts, notices, review articles, catalogs, and data summaries.

(7) At present, drilling is essential for successful HDR assessment. We recommend support for the research and development projects in improved heat flow techniques, borehole measurement technology, and slim hole drilling, which will improve acquisition of subsurface data.

(8) Continue to stress the use and applicability of heat flow surveys for HDR definition and assessment efforts. Insure that the interpretation of these data in conjunction with appropriate geological information and geophysical data, is realistic and provides for alternative interpretations of the heat flow regimes in the early phase of the assessment effort.

(9) Emphasize that powerful and simple geological tools are evolving for assessment of igneous-related systems based on the composition, volume, and age of volcanic rocks. This approach to the resource base assessment problem also needs to be developed aggressively.

(10) Research of the conduction-dominated HDR areas (such as the Basin and Range Province and much of the western U.S.) must proceed in parallel with the current emphasis on igneous-related geothermal systems. Future HDRAP reports should provide an overview of the knowledge of and probems associated with HDR assessment of these non-igneous related geothermal systems, i.e., basaltic volcanism, high heat flow regions, and HDR localities associated with large-scale tectonic features.

(11) Recognize that in order to understand the deep parts of active igneous-related geothermal systems, one or two very deep drill holes will be required. These holes should penetrate into the magma chamber, at anticipated depths of 4 to 6 km and temperatures of about 800°C. The most useful data will be obtained in drilling directly through the chamber roof. This has been documented in detail in the proposed U.S. Continental Drilling Program.

(12) Recognize that the development of HDR resource base assessment and characterization will require a long-term (7- to 10-yr) commitment.

(13) Aggessively extend and complete the investigations of the Valles Caldera and Marysville geothermal systems. Because both have deep boreholes, they are opportune sites for calibration of exploration methods. Furthermore, to date, neither project has been primarily concerned with the resource assessment. The crucial questions of heat source delineation, and constraint of geological models that identify hydrothermal and HDR portions of the systems, have not been quantitatively answered. Accomplishment of these tasks will require some broadening of the geophysical survey coverage, additional heat flow study, and slim hole drilling.

(14) Initiate, as soon as possible, appropriate HDR resource assessment base projects at the four recommended prime targets: Long Valley,

San Francisco Peaks, Mt. Shasta, and the Medicine Lake areas. These regional sites were chosen as representative of a spectrum of igneous- or volcanic-related geothermal systems. Assessment and characterization of their heat sources and associated hydrothermal and HDR systems will constitute a set of case histories from which other site assessments can be developed and, perhaps equally important, other similar high-grade HDR resource base sites can be assessed semi-quantitatively by analogy. These exploration programs will also form a valuable experience base upon which to assess the relative effectiveness of various exploration techniques, and to calibrate these techniques against sites with good working geological models.

(15) Continue to pursue vigorously the broadly based HDR assessment program under way at Coso. One major objective of this project is to define and delineate the heat source. By analogy to the Fenton Hill-Valles Caldera situation, it should be recognized that hot rock may exist on the flanks of the ring structure, as well as in the shallow blocks of crystalline rock adjacent to or even within the obvious, hydrothermal system near the center of the ring fracture. Testing of this possibility will ultimately require a slim hole through the deep (1-km) alluvial fill in the ring fracture area. Present research should be continued and should include (a) extended heat flow and slim hole drilling inside and outside the ring structure; (b) a deep-sounding magnetic-telluric survey with long base-lines ($\sim$ 100 km) and grid sufficient to search for the deep structure within and adjacent to the ring structure; and (c) extending the present resistivity grid radially outward and to greater depths to define the extent and nature of the hydrothermal portion of the geothermal system. The plans for the above expanded geophysical surveys and drilling program should consider the major fault zones on the west and south of the ring structure. These features may be major, deep sources of fluid for the hydrothermal system. This question should be considered in planning the geophysical surveys and the drilling programs because they may have cooled parts of

the geothermal system, and it is possible that the northern and eastern flanks of the structure may contain better prospects for HDR occurrence.

Also, we believe the slim hole drilling methods being developed at Coso will form an essential part of HDR resource base assessment techniques.

APPENDIX A
OTHER POTENTIAL HDR REGIONS

This appendix contains brief descriptions and maps of possible future sites for assessment of HDR resources.

A-1 Newberry Volcano, OR
A-2 Glass Buttes, OR
A-3 Crater Lake, OR
A-4 South Sister, OR
A-5 Northern Cascades, WA
A-6 Zuni Mountains, NM
A-7 Salton Trough, CA
A-8 Lassen Peak, CA
A-9 Clear Lake, CA
A-10 Island Park - Huckleberry Ridge Caldera, ID-WY
A-11 Yellowstone, WY
A-12 Mineral Range, UT
A-13 Tucson, AZ

Most of these are sites of the igneous-related type, and hence consitute the high-rank deposits of thermal energy. Although this list is representative, it is not intended to exclusively define potential HDR resource sites, nor is the order in which they are listed of any significance.

A-1. Newberry Volcano, OR

Newberry Volcano consists of a 40- by 64-km shield, about 900 m thick, with an oval, 7- to 5-km by 5-km caldera at the summit. The center of the shield is located at the intersection of the Walker Rim and Brothers fault systems. Higgins (1973) has petrologic evidence that a differentiated series of rocks within or close to the summit is evidence for a shallow magma chamber that formed at the junction of these fault systems. Preshield rock types are inferred to be high-alumina basalt flows, pyroclastic rocks, and sediments. The thickness of preshield rocks is unknown. Overall, the shield is very young; many of the rock units within the caldera are less than 6,000 yrs old and a few are less than 2,000 yrs old.

The most likely location for an HDR resource assessment is within or very close to the edge of the caldera, in analogy with the Valles Caldera situation. The surrounding rocks may be too open and permeable for HDR development and may contain a fluid convection system. The caldera itself is excluded from development because it is a popular recreational area. The shield, close to the caldera, might be promising because it is open for logging and grazing.

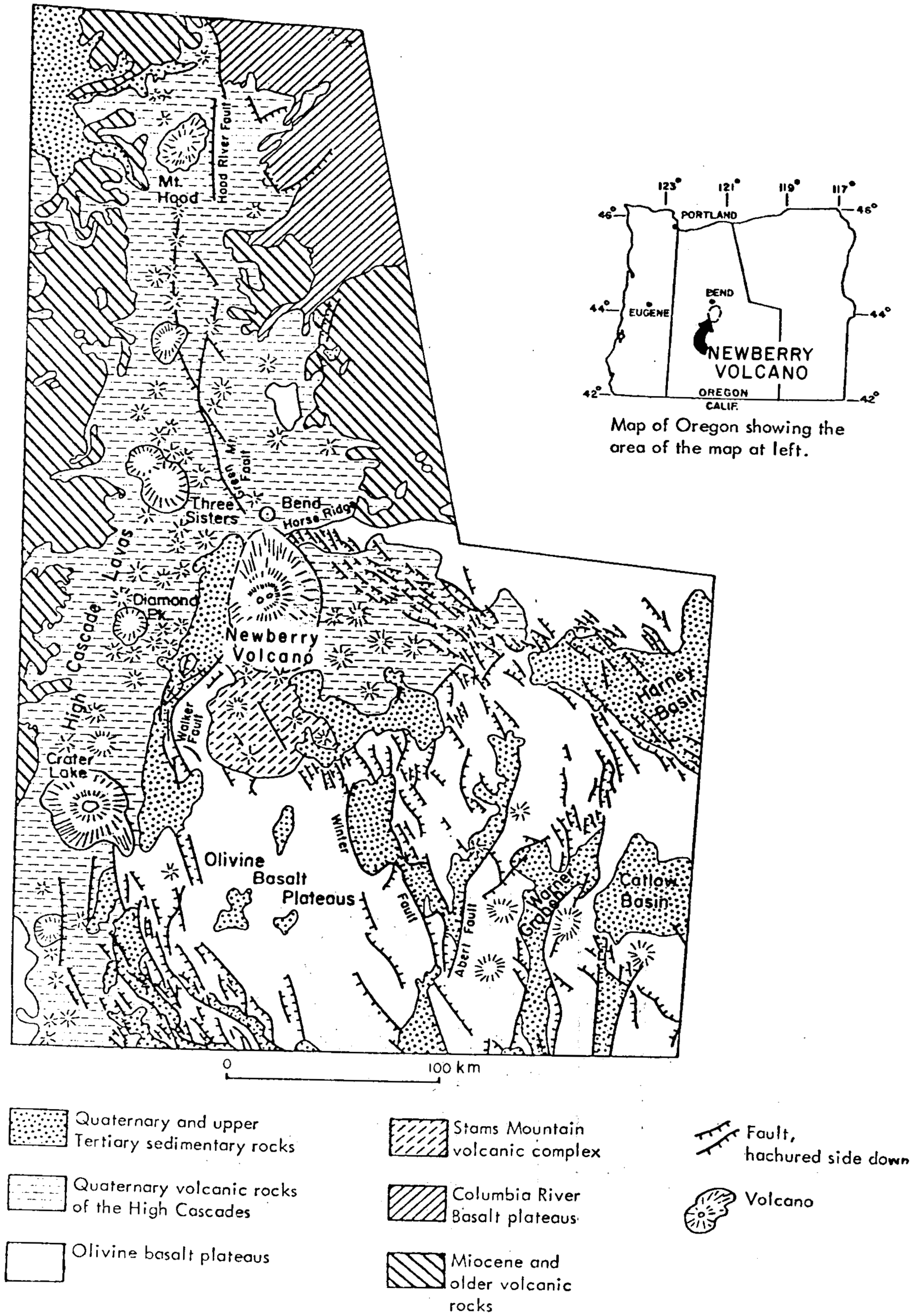


Figure A.1.1 Newberry Volcano, Oregon

A-2. GLASS BUTTES, OR

The Glass Buttes consist of a complex of silicic domes and flows, late Cenozoic in age, which overlie plateau basalts. The complex has been dated as 4.9 ± 0.73 m.y. It is part of the line of silicic centers located along the southeast-northwest trending Brother's fault zone, which ends at Newberry Volcano. Silicic domes younger than 11 m.y. occur along this 250-km-long belt which shows a well-defined age progression from less than 1 m.y. at Newberry Caldera to 10 m.y. in the east (MacLeod et al., 1975). Observed heat flow is 1.5 to 2.0 HFU; a thermal anomaly of about 30 km^2 has been observed in the area of Glass Buttes. Recent gravity and resistivity surveys were made by the State of Oregon (Anon., 1976). There may be silicic intrusive bodies young enough to serve as heat sources for geothermal systems.

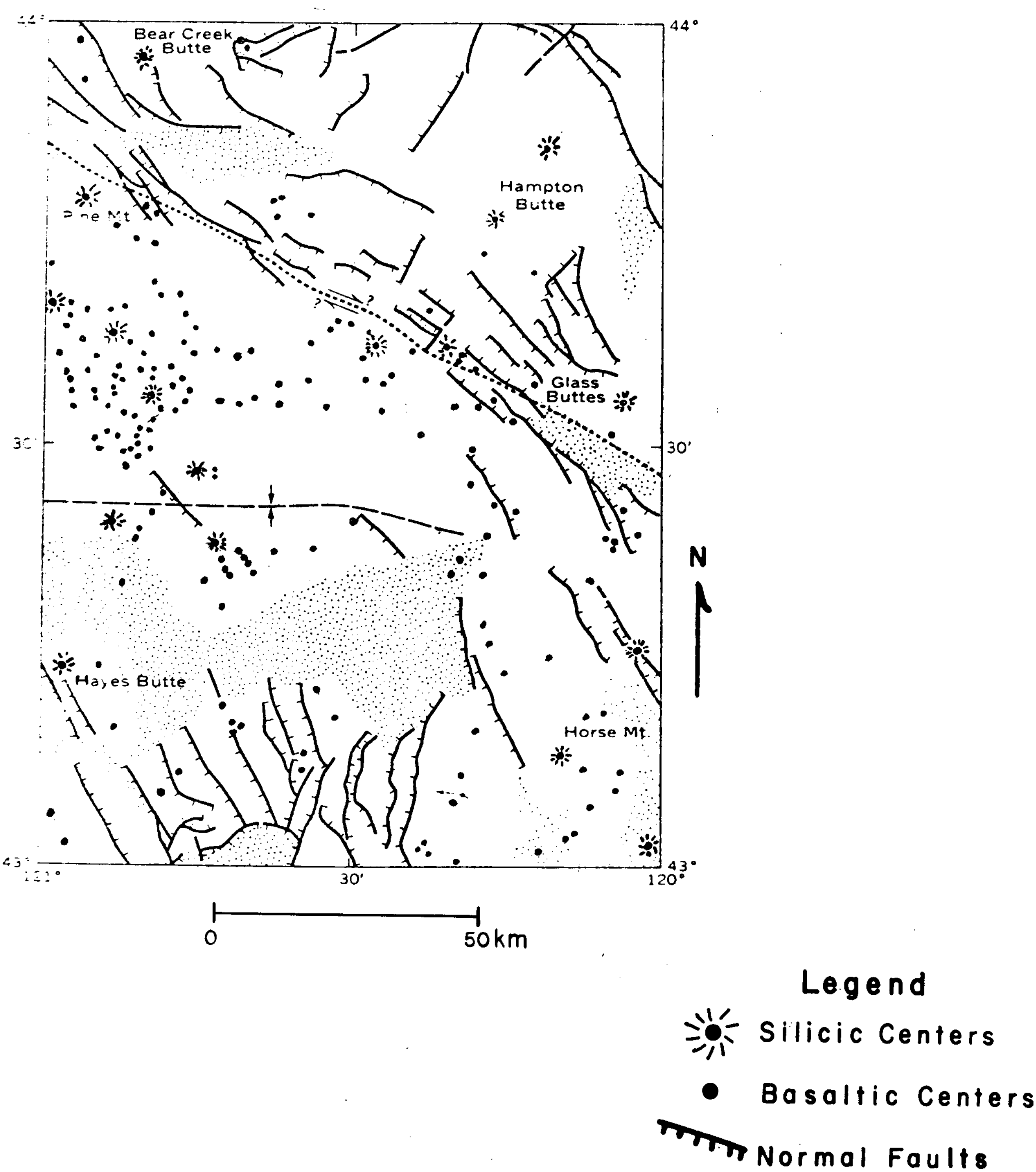


Figure A.2.1 Glass Buttes, Oregon

A-3. CRATER LAKE REGION, OR

The Crater Lake caldera formed by collapse of a large stratovolcano of intermediate composition during a large ash-producing eruption 6,600 yr ago. The total volume of tephra erupted was about 42 km^3. Since the eruption and collapse 6,600-yr ago, several dacite domes and andesitic cinder cones erupted from the crater floor.

Crater Lake is located astride a broad upwarp of crystalline rocks that is presumed to extend northeast from the Klamath Mountains. There is no direct evidence for the nature of rock types underlying the area, but there are xenoliths of partly melted granodiorite within the tephra erupted 6,600 yrs ago. A positive magnetic and negative gravity anomaly with circular symmetry in the Cascades west of Union Peak may be associated with an as yet unknown older volcanic center (Blank, 1968).

There is abundant geological and geophysical data available for this area (gravity, magnetic, and microseismic surveys), but no heat flow surveys have been made.

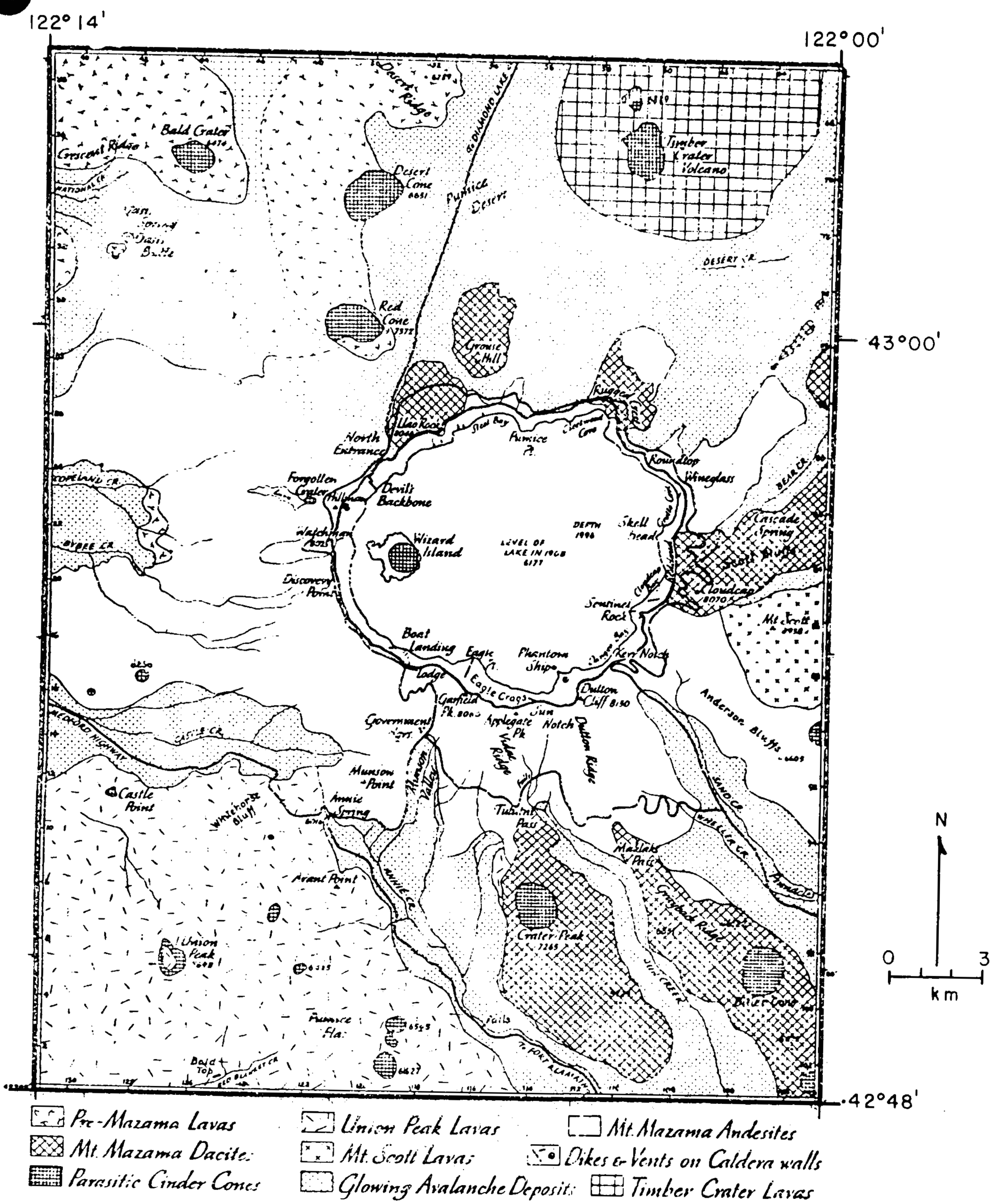


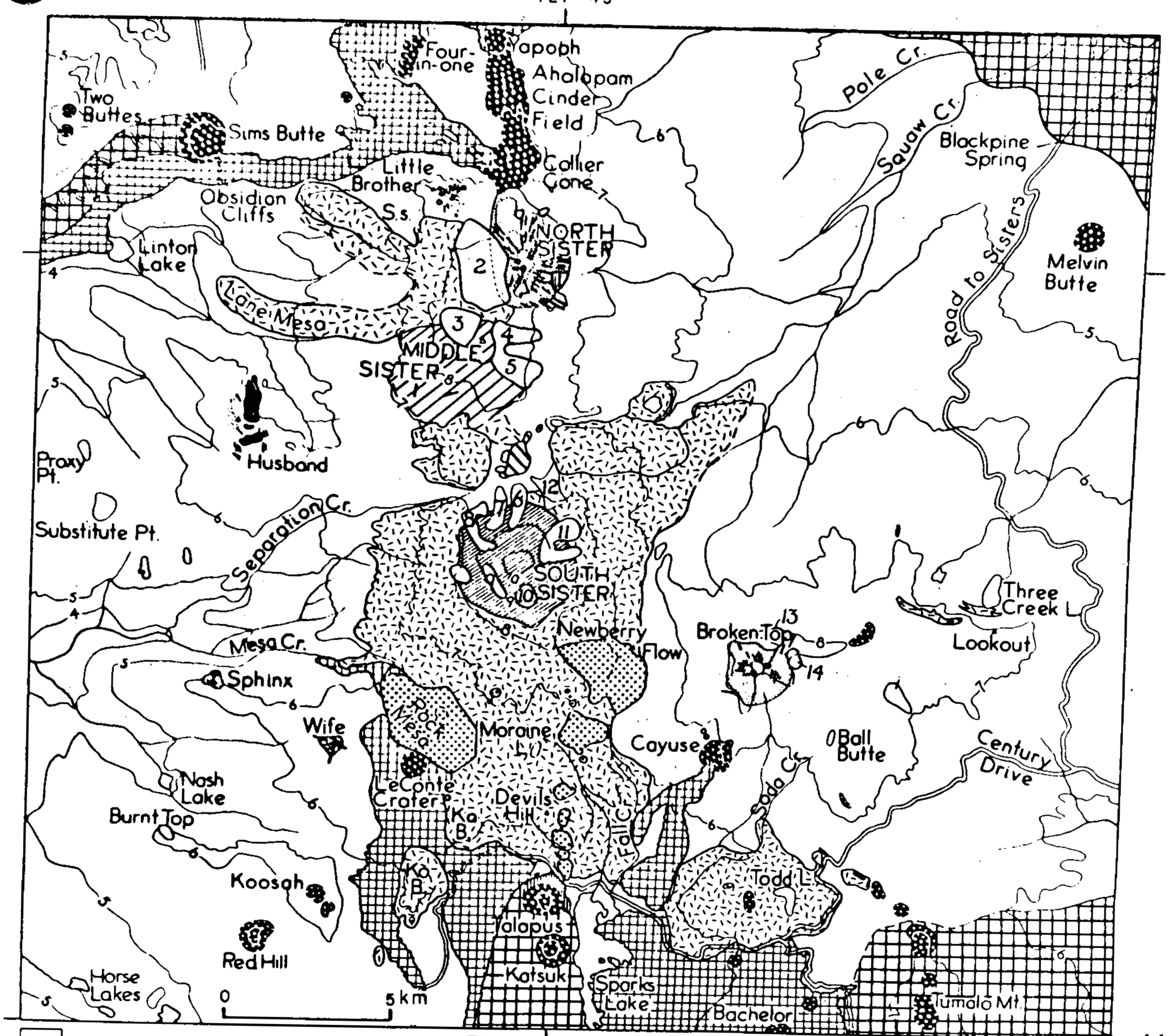
Figure A.3.1 Crater Lake, Oregon

A-4. SOUTH SISTER, OR

South Sister volcano is one of a cluster of Late Tertiary to Recent volcanoes on the crest of the Cascade Range west of the city of Bend, OR. The volcanoes overlie a sequence of Eocene to upper Miocene lavas and sediments. Nothing is known of rocks older than the Late Tertiary lavas; no xenoliths of the older "basement" rocks have been recognized in lavas of the volcano.

South Sister developed first as a basaltic shield, overlain by a steeper composite cone of andesite and dacite flows that are capped, in turn, by basaltic cinder cones. A chain of dacite domes and flows erupted along a fissure on the southeast slope of South Sister. The South Sister is the youngest volcano in the Three Sisters region, with some flows estimated to be less than 2,000 yrs old.

Detailed geologic mapping, more age dates, and geophysical surveys are needed in this region before any HDR resource base can be estimated.



Basic lavas of old shield volcanoes; Summit cones; Plugs; Dikes; Glaciated andesites & dacites; Dacite pumice; Younger basalts of the Middle Sister; Older unglaciated basalts; Summit cones of South Sister; Tuff breccias of Talapus Butte; Scoria cones; Most recent basalts; Recent obsidians; Glaciers No. 1 - Thayer; 2 - Collier; 3 - Renfrew; 4 - Hayden; 5 - Diller; 6 - Skinner; 7 - Eugene; 8 - Lost Creek; 9 - Clark; 10 - Lewis; 11 - Prouty; 12 - Carver; 13 - Bend KaB - Kaleetan Butte; KoB - Kokostick Butte; S.s. - Sunshine shelter. Contour interval, 1,000 feet. Topography from Three Sisters Quadrangle, U.S.G.S.

Figure A.4.1 South Sisters, Oregon

A-5. NORTHERN CASCADE RANGE, WA (Including Mt. Baker, Mt. Rainier, Mt. St. Helens, and Glacier Peak)

The Cascade Range is the most active area of recent volcanism in the continental U.S. In the northern Cascade Range, a belt of plutons and batholiths, representing roots of ancestral Cascade volcanoes, extends along the range crest. The dominant rock type is relatively homogeneous granodiorite. One of the best exposed of the batholiths is the Snoqualmie, with an exposed area of 700 km^2, located 50 km east of Seattle (Erikson, 1969). Less well-exposed plutons are associated with the Glacier Peak, Mt. Baker, Mt. Rainier, and Mt. St. Helens Quaternary stratovolcanoes. Except for Glacier Peak, the volcanoes have had eruptions within the last 1000 yr and have active hydrothermal systems.

Although there is a lack of geophysical data, especially heat flow, the pluton belt has some obvious advantages for HDR development. (1) The geology is well known and the basement rock types ideal, (2) the heat flow should be high because the plutons lie along the crest of an active volcanic range, and (3) the belt is near areas of dense population.

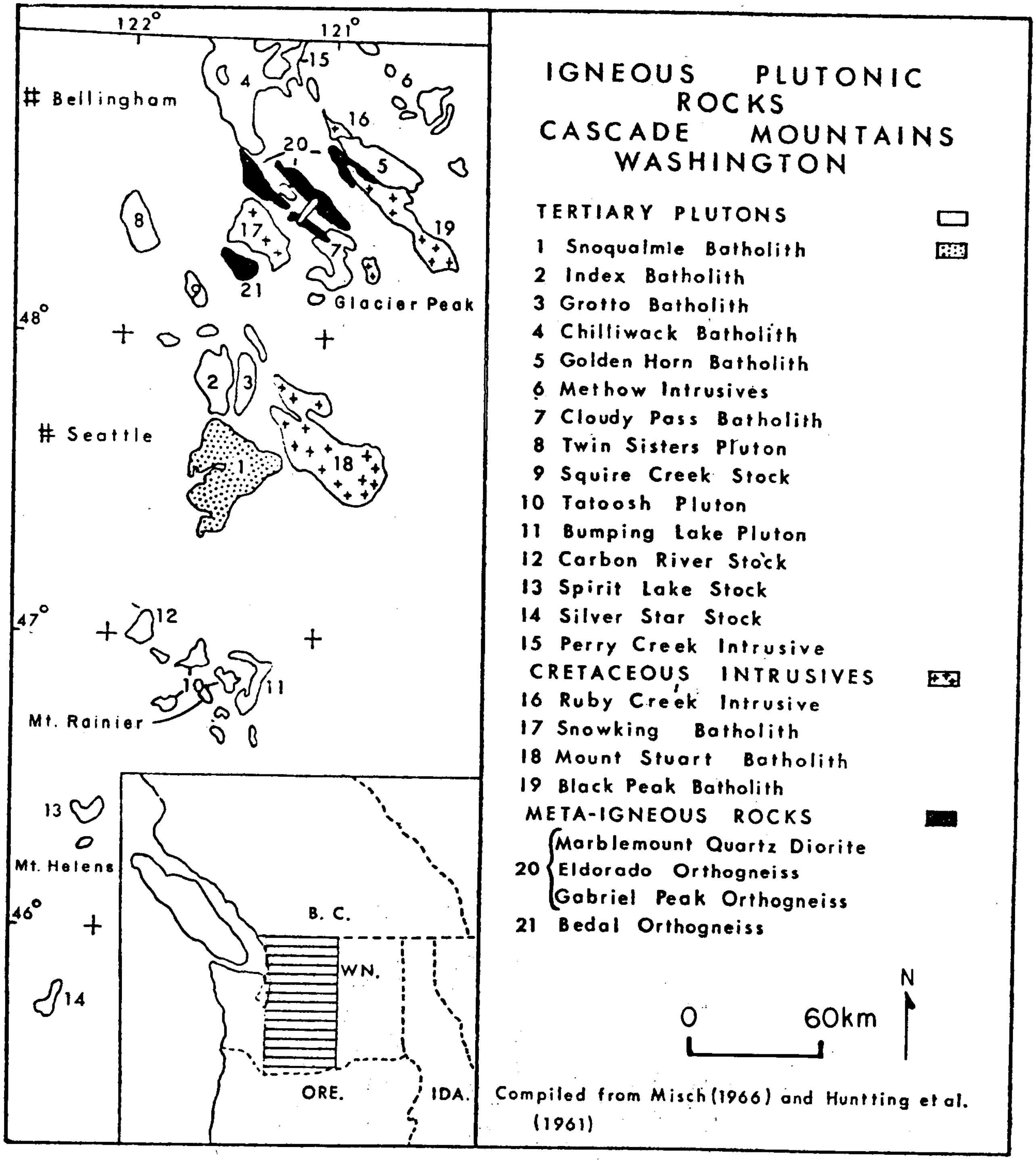


Figure A.5.1 Northern Cascade Range, Washington

A-6. ZUNI MOUNTAINS AREA, NM

The Zuni Mountains constitute a large region ($\sim$ 16 by $10^3 km^2$) in west-central New Mexico characterized by high regional heat flow (<2.5 HFU). They consist of a dissected anticline with a Precambrian core. Trending northeast through the area is a linear belt of late Cenozoic basaltic volcanoes ranging in age from 3 m.y. to 700 A.D. At Mt. Taylor, at the northeast end of the area, differentiation has produced a suite of volcanic rocks ranging in composition from basalt to rhyolite. Within the Zuni Mountains volcanic rocks are eroded; therefore, they are well exposed and also range in composition from basalt to rhyolite. Basaltic volcanoes lie along the east and south sides of the anticline and along north-south faults crossing the northwest trending axis of the anticline. On the southwest flank of the anticline there is a 43- by 55-km negative gravity anomaly, which may indicate a buried felsic pluton as is inferred to underly Mt. Taylor and the Valles Caldera (Laughlin and West, 1976).

The Precambrian rocks of the Zuni Mountains have been mapped by the U.S.Geological Survey. The basalts have been mapped by A.W. Laughlin and his students and dated by Damon and Laughlin.

Additional heat-flow measurements need to be made and other geophysical surveys accomplished before specific areal or local sites can be selected for detailed resource base assessment.

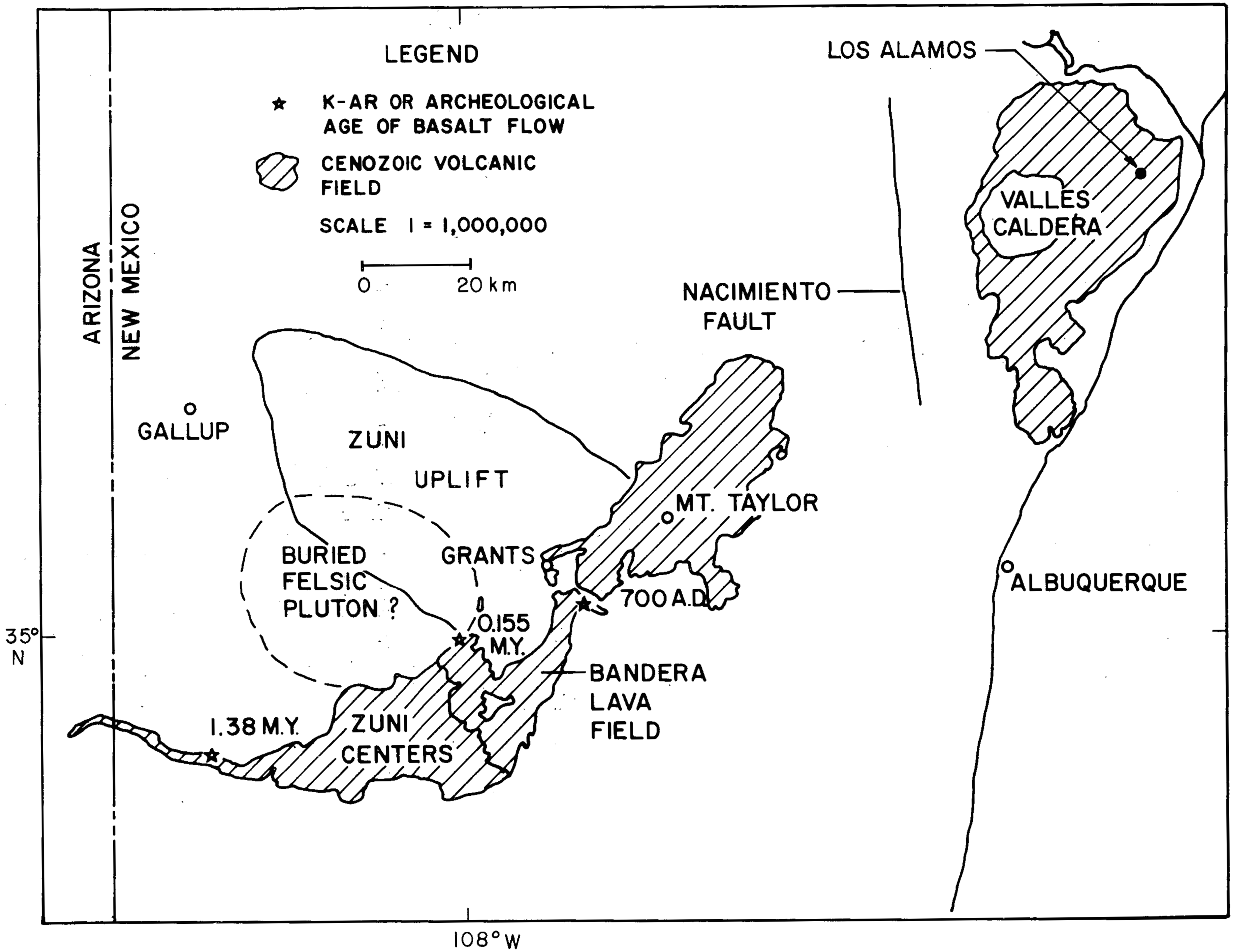


Figure A.6.1 Zuni Mountain Area, New Mexico

A-7. SALTON TROUGH, CA

The Salton Trough, CA, has long been recognized as a geothermal area, but attempts at development have been hindered by the high salinity of the geothermal fluids. This problem could be avoided by the HDR technique; although the trough is filled with 2 to 6 km of sediments, it is possibly underlain by granitic basement. This conclusion is supported by the presence of granite xenoliths in the lavas. The high heat flow is related to Quaternary (as young as 16,000 yr) volcanism and a thin (>10-km) crust. Temperature gradients greater than 200°C/km and abundant, partly melted granite xenoliths in rhyolites suggest that magmatic temperatures occur at relatively shallow levels in the crust (Robinson et al., 1976). The most difficult problem is the high seismic activity and recent faulting within the crust. There are sufficient geological and geophysical data to choose sites for exploratory deep drill holes to reach basement.

The nature of the heat source is not precisely known and is of considerable interest because it is possible that shallow plutons, without surface volcanic rocks, may be present. Furthermore, the area involves the intersection of the landward extension of the mid-ocean ridge system (the East Pacific rise) with the continent, in a very complex way. The complexity arises because the Salton Sea area is part of a broad zone about 50 km wide containing three branches of the southern extension of the San Andreas fault system; this fault system defines the junction of two major crustal plates. Hence the origin of the potenital HDR resources is the consequence of a complex and very interesting tectonic environment -- it is not clear in which category of HDR resource sites the Salton Trough would fit.

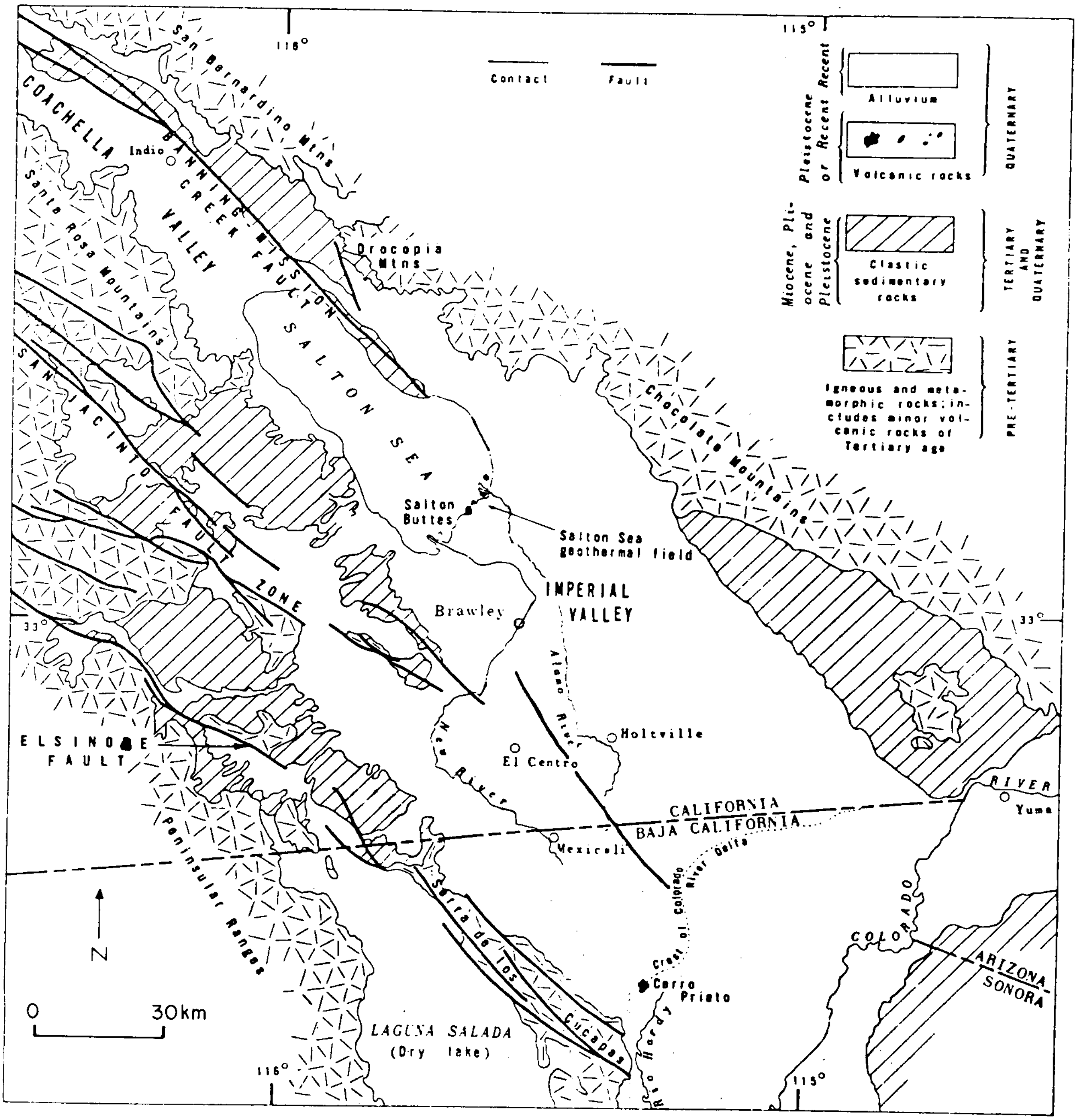


Figure A.7.1 Salton Trough geothermal area, California

A-8. LASSEN PEAK AREA, CA

Lassen Peak is the southernmost active volcano of the Cascade Range. The volcanic highland around Lassen Peak includes thick andesite flows and cinder cones, four andesitic shield volcanoes, remnants of a composite andesite shield volcano and a series of large dacite domes. The Brokeoff Peak cone has extruded large volumes of dacite, the largest of which is Lassen Peak. Recent volcanic activity includes the eruption of the Chaos Crags ash deposits and domes, 1,200 yr ago, andesite flows near the base of Prospect Peak in 1851, and the eruption of Lassen Peak from 1915 to 1921. There are numerous thermal areas, including Bumpass Hell, in the Brokeoff caldera, which contains one of the few superheated steam vents in the Cascade Range. The area coincides with a gravity low that has been interpreted as a large silicic intrusive body located under the volcanic field.

Little is known of the rocks underlying the region. The oldest rocks visible in the region are Cenozoic andesite flows and sediments. It is possible that the Silurian to Jurassic age sedimentary rocks extend north, from where they are exposed in the northern Sierra Nevada, to underlie the Cenozoic volcanic sequence.

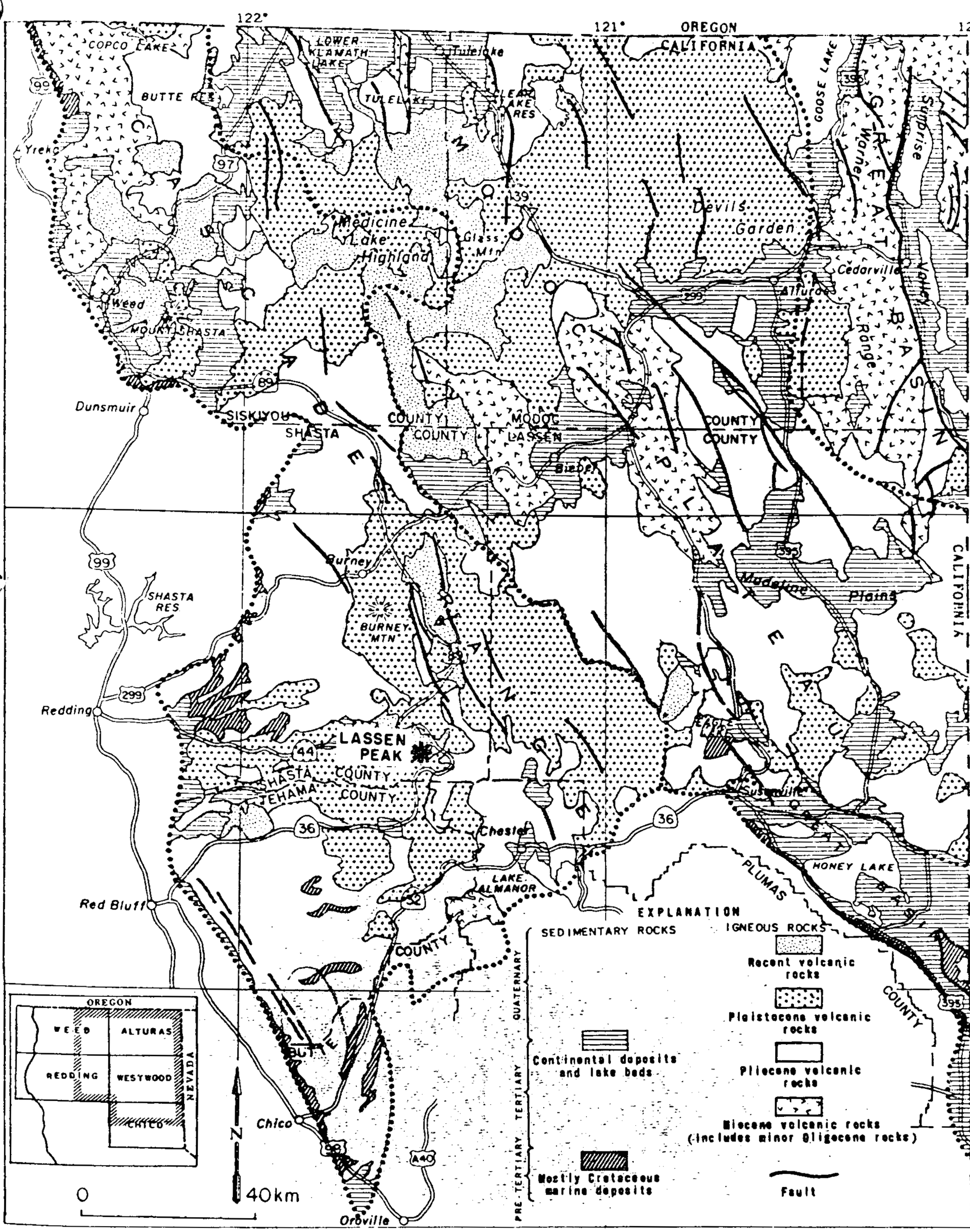


Figure A.8.1 Lassen Peak, California

A-9. CLEAR LAKE, CA

The Clear Lake volcanic field is located in the northern coast ranges of California, 145 km north of San Francisco. The field has been active from about 2.5 m.y. to less than 10,000 years B.P.. Compositions range from basalt to rhyolite; some sequences suggest changes in magma composition from basalt through dacite to rhyolite (Hearn et al., 1975). The most recent activity produced cinder cones and maars.

There is current deformation of the field along northwest trending faults with inferred strike-slip offset. There are also many normal faults trending northeast and northwest.

Gravity and resistivity lows are interpreted as being related to an underlying, partly fluid magma chamber (Hearn et al., 1975). The volcanic field overlies upper Cretaceous sedimentary rocks, a Franciscan assemblage, and the Sonoma volcanic sequence (Anderson, 1936).

The youth of the volcanic rocks and the presence of thermal springs imply that the field has geothermal potential (Hearn et al., 1975).

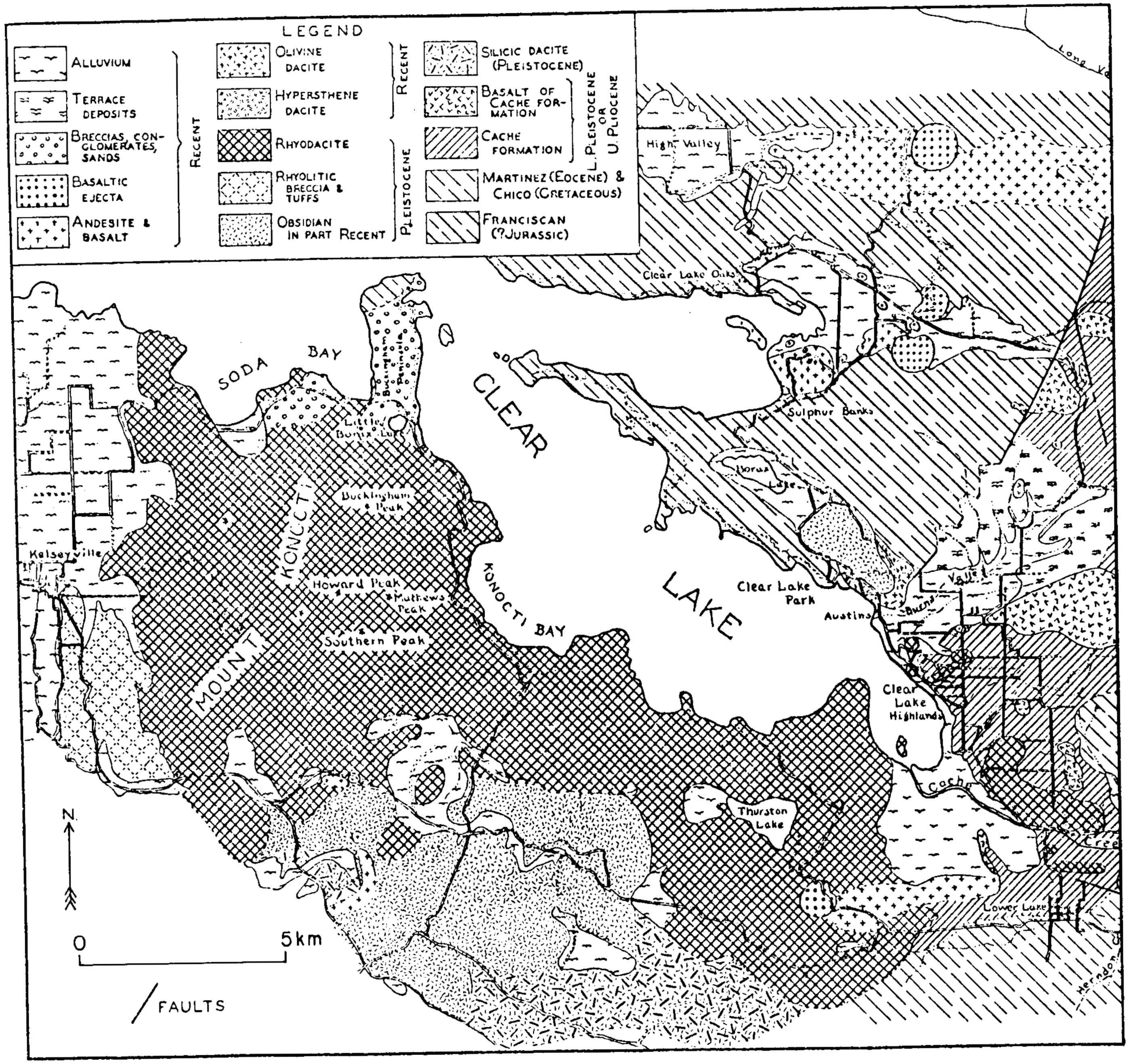


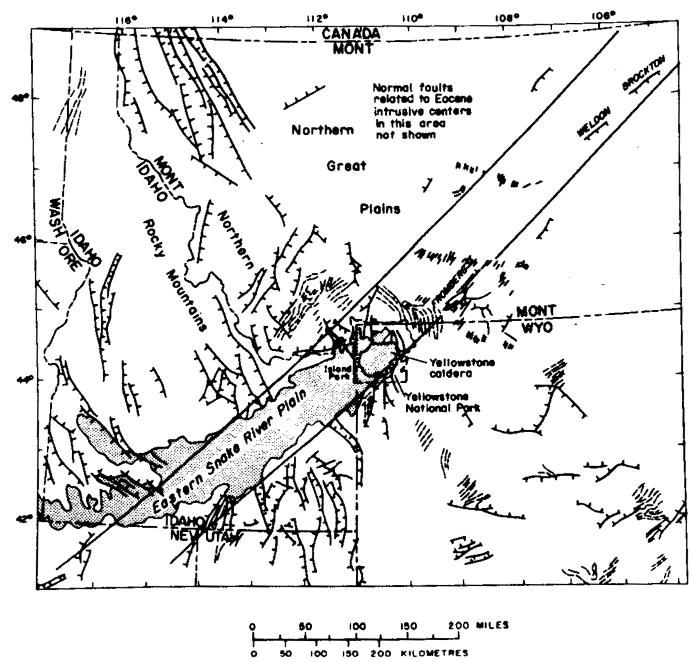
Figure A.9.1 Clear Lake, California

A-10. ISLAND PARK - HUCKLEBERRY RIDGE CALDERA, ID - WY

Island Park is a topographic basin of compound origin related to the three rhyolitic cycles of the Yellowstone Plateau volcanic field. The Southwestern rim of Island Park bounds a segment of the first-cycle caldera that formed by collapse during the Huckleberry Ridge tuff eruption 1.9 m.y. ago. The northwest rim of Island Park bounds a segment of a second-cycle caldera 20 km across that formed 1.2 m.y. ago as a result of the Mesa Falls tuff eruption.

Much of the first- and second-cycle calderas are buried by the third-cycle 0.6-m.y.-old Lava Creek tuff and younger volcanic rocks. The eastern rim of Island Park is not a caldera scarp but the edge of large rhyolite flows of the third cycle (Christiansen, 1975).

The youngest rhyolitic eruptions at Island Park occurred about 1 m.y. ago. Basaltic magma has erupted through the caldera floor during the last 300,000 yr. Granitic plutons in the region are cooling and a geothermal resource might exist at moderate depth (Christiansen, 1975).



Regional tectonic map showing relation of Yellowstone National Park region to the eastern Snake River Plain, northern Rocky Mountains, and northern Great Plains. The words *Island Park* mark the site of the caldera of that name. Heavy parallel lines represent boundaries of the regional aeromagnetic anomaly zone.

Figure A.10.1 Island Park-Huckleberry Ridge, Idaho-Wyoming

A-11. YELLOWSTONE PLATEAU, WY - MT - ID

The Yellowstone plateau volcanic field is less than 2.0 m.y. old and lies in a region of intense tectonic and hydrothermal activity. The youngest volcanic cycle climaxed 0.6 m.y. ago with a large ash-flow eruption and collapse to form a volcanic cauldron. Rhyolitic lavas were erupted as recently as 70,000 yr ago.

There is high convective heat flow in the region at present. A major gravity low with steep bounding gradients is coincident with the cauldron boundaries. The gravity, plus attenuation of seismic waves below the caldera, suggests the presence of a body, composed at least partly of magma, underlying the volcanic field (Eaton et al., 1975).

The rocks immediately under the volcanic plateau may consist, in part, of Precambrian gneiss and granite; there are gneissic xenoliths within some of the lavas and Precambrian terrane exposed south and north of the volcanic field. The area west of the caldera, outside the National Park boundaries, has been suggested as a potential HDR regional site.

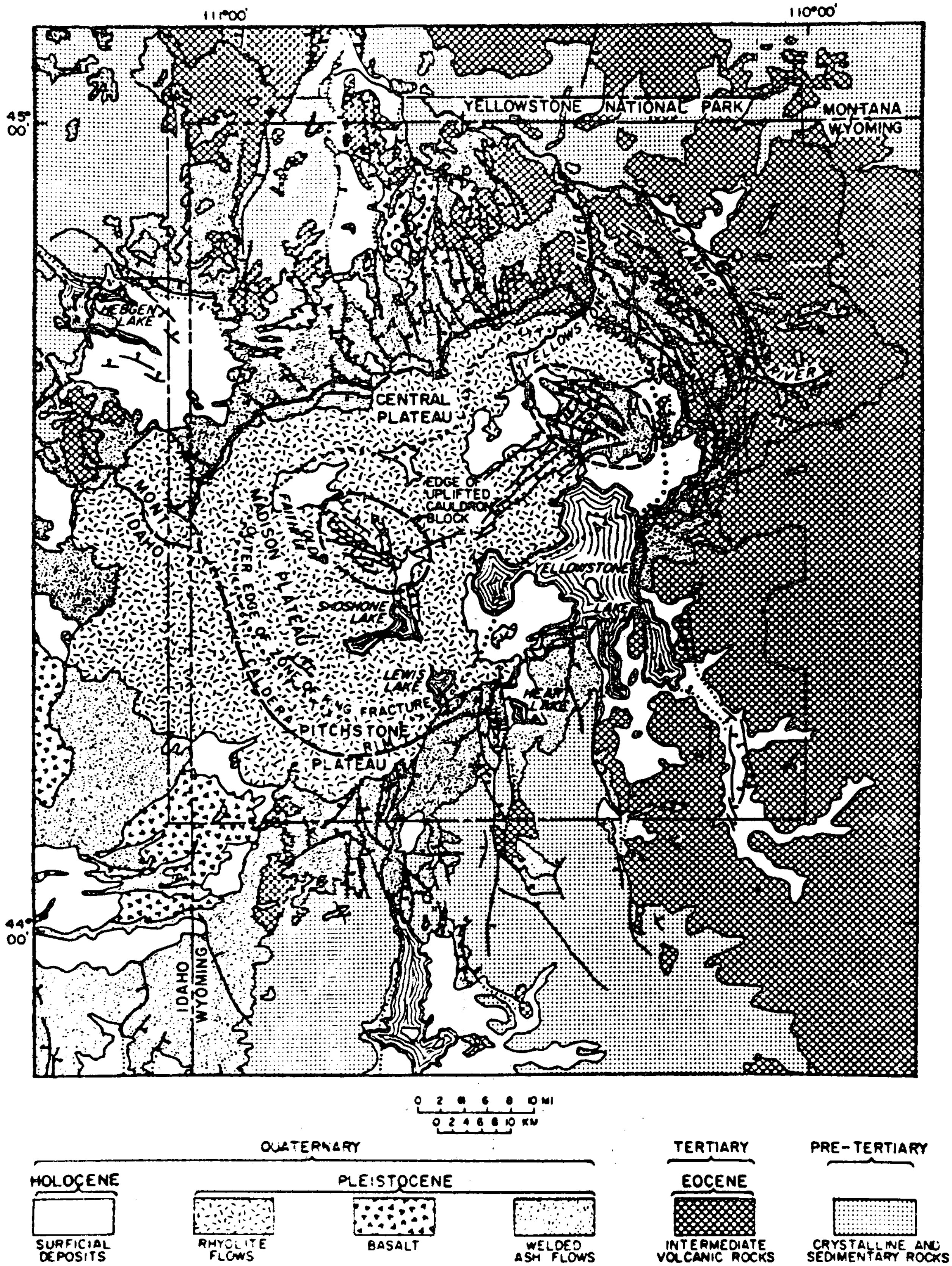
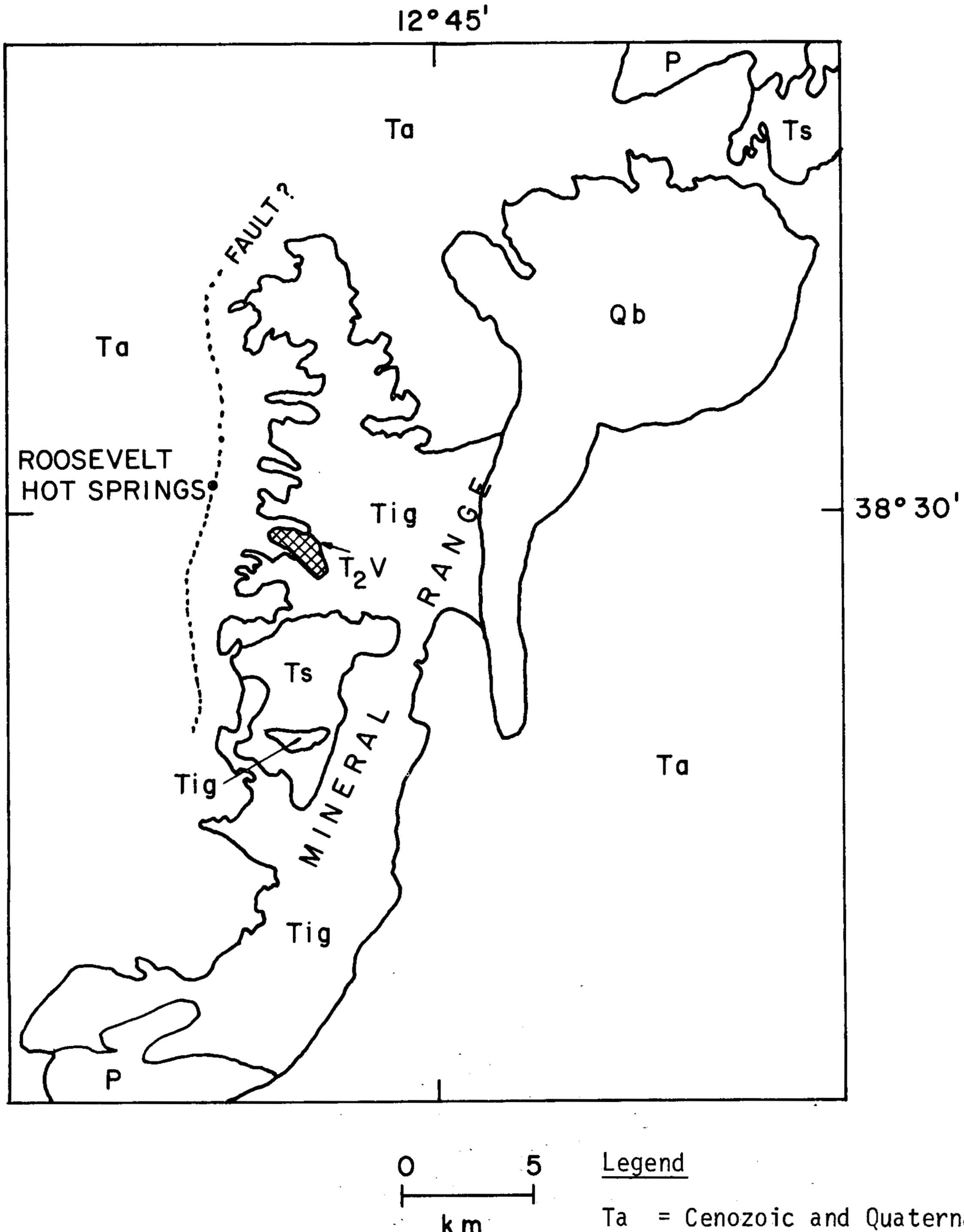


Figure A.11.1 Yellowstone Plateau, Wyoming-Montana-Idaho

A-12. THE MINERAL RANGE, UT

The Mineral Range, located just west of Beaver, UT, has been the site of sporadic mining for many years. The core of the range consists of Tertiary granites, making up the largest intrusive body exposed in Utah. Rhyolitic volcanism began about 1 m.y. ago, with vents located near the crest of the range. The recent volcanic deposits consist of silicic ash-flow tuffs, domes, and flows (Lipman et al., 1975).

The vent areas are within 5 km of the Roosevelt Springs KGRA. Ceophysical surveys of the region are being made by the University of Utah.



Legend

Ta = Cenozoic and Quaternary Sedimentary Rocks

Tig = Tertiary Intrusive Rocks

Qb = Quaternary Basalt

Ts = Cenozoic Silicic Flows

P = Paleozoic Sedimentary Rocks

Figure A.12.1 Mineral Range, Utah

A-13. TUCSON AREA, AZ

A large area south and southwest of Tucson, AZ, is characterized by high heat flow. Fifteen measurements have an average of 2.12 HFU and a range of 1.82 to 2.97 (Sass et al., 1971). Because of interest in the copper porphyry deposits, the area has been well mapped by the U.S.G.S., Arizona Bureau of Mines, the University of Arizona, and various mining companies. The area lies within the Basin-Range Province with most of the ranges being made up of Laramide age plutonic and mid-Tertiary age volcanic rocks. Basalt flows of Quaternary age are present at several localities within the area. The Laramide plutonic rocks are potentially useful reservoir rocks because of multiple periods of mineralization, which may have yielded low-permeability rocks at depth. Compilation of available geologic and geophysical data is needed before any additional geophysical work is done.

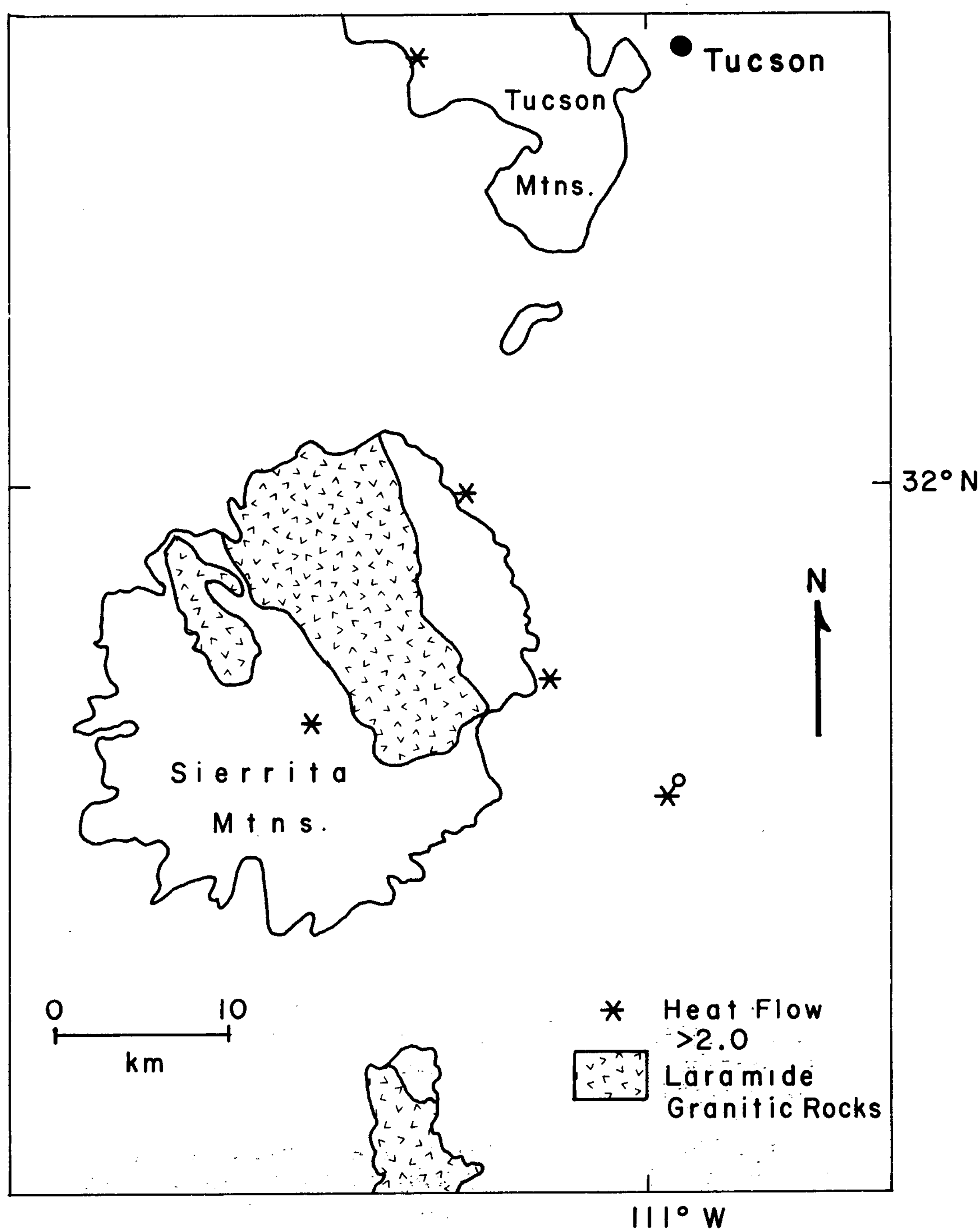


Figure A.13.1 Tucson Area, Arizona

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APPENDIX B

EXCERPT FROM CONTINENTAL DRILLING

This appendix contains pages 14 through 21 of Continental Drilling, E.M. Shoemaker, editor, Report of the Workshop on Continental Drilling, Ghost Ranch, Abiquiu, New Mexico, 10-13 June 1974, E.M. Shoemaker and G.A. Swann, Conveners, Carnegie Institute of Washington, 56 p., Issued June 1975. This section of the Ghost Ranch report is entitled "Hydrothermal Systems and Active Magma Chambers." It contains a detailed description of the scientific and practical reasons for deep drilling into active geothermal systems. Although not written with the intention of addressing the HDR assessment problem, much of this discussion bears directly on it.

ACTIVE MAGMA CHAMBERS

The scientific and economic potential of a program of drilling into an active hydrothermal-magmatic system is enormous. Drilling into such a system is likely to lead to significant improvements in exploration for geothermal energy and hydrothermal mineral deposits, especially copper, lead, zinc, and molybdenum. Totally new scientific insights would be obtained with regard to (1) problems of crystallization of magma, (2) interactions between magma and country rock, (3) amounts of dissolved volatiles and evolution of gases from the magma and from the contact-metamorphosed zones around the magma chamber, (4) possible migration of H_2O and other volatiles from the country rocks into the magma, (5) the mechanisms of heat transfer in the immediate vicinity of the magma body, (6) the convective circulation of pore waters in the country rocks, (7) the state of stress and strain in the wall rocks adjacent to a magma chamber, (8) development of instrumentation for predicting the time, location, and violence of volcanic eruptions, and (9) the development of ore-forming fluids.

Magmas have been investigated in their natural state at the earth's surface in volcanic areas, and they have also been studied in the laboratory under a wide range of conditions of T, P, f_{O_2}, and P_{H_2O}. Crystallized magmas (i.e., igneous rocks) and associated ore deposits have also been studied throughout the world, in both volcanic and plutonic terranes. The next great advance in our understanding of igneous processes and associated hydrothermal phenomena must come from direct investigations of an active magma chamber, where we can measure the conditions and determine compositions in place, studying the dynamic phenomena as they happen. Almost all previous petrologic studies have been forced to infer the nature of the aqueous fluids and silicate melts from studies of the rocks long after they had formed.

Most plausible localities for studies of this type are also areas of potential or actual development of geothermal power. Beyond intrinsic scientific interest, it is important to understand deep parts of economically important geothermal systems. Information not obtainable by relatively shallow commercial drilling is needed to evaluate the ultimate resource potential of a given locality, and the economic potential of less-developed geothermal areas. The feasibility of obtaining energy directly from the magma, or from the very hot contact zone around the magma, also can be investigated in this type of research.

The basic scientific objectives of a hydrothermal-magmatic drilling program are grouped below on the basis of proximity to the magma chamber:

1. The shallow hydrothermal zone (perhaps ⅓ to 3 km). This zone has been drilled extensively in recent years, primarily for geothermal power. The intense scientific value and interest in commercially developed sites dictate that every effort be made to make relevant data available to the scientific community at the earliest possible date. Additional holes in this zone are needed to obtain observations of fundamental importance that are unavailable from the wells drilled by industry.

2. The deep hydrothermal or conductive-transfer zone (from 2 to 3 km down to the contact between the magma body and the country rock perhaps at about 3 to 6 km). The nature of this zone is scarcely known at present. All data obtained in this environment will be of great scientific interest. Major emphasis should be placed on understanding temperature and pressure gradients, fluid movements, heat-transfer mechanisms, water-

rock interactions, and amounts and chemical and isotopic composition of the water moving through this zone.

3. The magma chamber contact zone (at about 3 to 6 km depth). Because of high temperatures (in the range of 800°–1000°C), this zone represents the most difficult drilling and sampling problem. Even if the hole penetrates within only a few meters of the magma, a great deal of information could be obtained on chemical transfers near the contact. Major emphasis here will be placed upon quantitative understanding of transfers of gases, sulfur, alkali metals, volatile heavy metals (Pb, Hg, Bi, etc.), and, in particular, H_2O. It is hoped that the dynamics of contact metasomatism and contact metamorphism in the contact zone can be studied. Chemical gradients in the magma, and various important parameters that characterize the magma (P_{H_2O}, P_{O_2}, T, P, viscosity, convective motion, etc.) will all be studied either *in situ* or after samples are brought to the surface. Tracer experiments should allow monitoring of the dynamics of transfers at the magma–wall rock interface.

4. Magma chamber zone. Should it prove feasible to extend the drill hole into the actual magma chamber, there are a number of experiments and measurements that might be performed. First priority would be the collection and return of samples of magma and any volatile phases as well as *in situ* measurements of temperature and pressure. *In situ* experiments to measure the dynamic state of the magma and material-transport mechanisms would also be of great interest.

Feasibility of the Proposed Drilling and Experimental Program

Conventional drilling techniques are applicable to investigation of the shallow meteoric-hydrothermal zone. Most of the deep hydrothermal or conductive-transfer zone around a magma chamber probably can be studied with modifications of existing drilling techniques. Major advances in instrumentation will be necessary, however, in order to obtain appropriate measurements at the high temperatures in this zone. Much of the scientific investigation of the deep hydrothermal zone discussed below could be pursued with intermediate-depth drill holes. Because these holes provide important preliminary tests of the feasibility of drilling more deeply, to the magma chamber itself, as well as providing valuable data immediately, they should be started early in the program.

For great depths, new drilling and data-gathering technology must be developed. It is likely that double-layered, water-cooled casing of the drill hole will be necessary. In very hot rocks, completely new and unconventional forms of drilling will be needed. The problems of developing new techniques to penetrate the contact zone of the magma body or even the magma itself are difficult but not insurmountable. Because of the cost of deep or experimental drilling and the development of its associated technology, multi-purpose sites should be considered, with initial emphasis on the shallower, hydrothermal parts of the system.

The process of drilling a hole perturbs the geologic conditions in the vicinity of the hole. Thus some scientific data of interest will be affected by the methods of gaining access and making the measurements. The extent to which the effects of drilling can be controlled or accounted for is a problem that will require considerable research.

Scientific Objectives in the Deep Hydrothermal Zone

Different types of hydrothermal systems. Present-day geothermal systems can be conveniently divided into two types: (1) vapor-dominated or dry-steam systems such as are found at the Geysers, California, and Larderello, Italy; and (2) hot-water geothermal systems such as that found at Wairakei, New Zealand. The vapor-dominated systems currently are considered most favorable for geothermal energy development, but the hot-water systems are more common. Where solutions are very saline (as in the Salton Sea area, California), the explored portions of some hot-water systems attain temperatures as high as 350°C.

The deeper hydrothermal zones of these two broad types of geothermal systems have never been scientifically explored. Many hypothetical models of such systems have been formulated, but quantitative data must be obtained in order to evaluate them. Because of possible fundamental differences in the processes driving vapor-dominated and hot-water systems and because each system appears to have unique characteristics, a knowledge of the deep parts of both is essential.

Physics of geothermal systems. The nature of the heat transfer mechanism in geothermal systems is one of the fundamental problems that can be approached by means of drill holes. Geothermal reservoirs are characterized by coupled mass and energy transport; energy is transported both conductively and convectively (by moving fluid). In many reservoirs, fluids exist both as liquid and vapor; energy is exchanged between phases as well as transported by phases.

Understanding a geothermal system requires a three-dimensional knowledge of the distribution of temperature and pressure, together with knowledge of fluid motion. To solve for conductive energy transport, it is necessary to know the thermal conductivity and heat capacity of the rocks. Determination of convective energy transport requires a knowledge of fluid velocity, the thermal dispersivity of the medium, and the behavior of multi-component liquids and gases. The fluid motion is controlled by (1) pressure of the fluid, (2) density (chemical composition) of the fluid, (3) permeability of the medium (both fracture permeability and matrix permeability), and (4) compressibility of the rock-fluid system. The physical parameters of the system can vary in three dimensions. Some parameters are difficult to measure because of extreme variability (e.g., permeability varies over ten or more orders of magnitude). Because such parameters as permeability are commonly dominated by *in situ* properties of the rocks in many geothermal systems, they must be measured *in situ.*

To fully define the system, it is necessary to measure the following state variables: (1) pressure (*in situ*), (2) temperature (*in situ*), and (3) fluid composition (*in situ* fluid sample). Conductive heat flow to and from the boundaries of the system must also be known. In addition, several physical characteristics of the system must be determined. These include: (1) rock composition (core), (2) thermal conductivity (core), (3) permeability (*in situ* and laboratory), and (5) thermal dispersivity (eddy diffusion–diffusivity *in situ*). Except for thermal dispersivity, technology is available to isolate a specific section of the drill hole, using packers, to make the necessary measurements of fluid pressure, permeability, compressibility, and to recover a fluid sample at temperatures up to about 250°C. Temperatures within this range are readily measured, except in those instances in which (1) fluid is moving in the hole, or (2) an equilibrium temperature may not have been reached.

The geometry of the geothermal system and the interaction of the circulating waters with the rocks cannot be solved with shallow drill holes alone, or even with a combination of shallow drill holes and a single deep hole. At least two deep holes should be drilled, one located over the center of the magma chamber and the other on the flank. Two such holes would provide much more information than a single hole on both the deep hydrothermal circulation and the spatial variations of composition, particularly of volatiles, within a magma chamber.

Interchange of volatiles between magma and the country rock. One of the most important geologic problems to be solved concerns the source of deep hydrothermal fluids around a magma chamber: the relative amounts and roles of true magmatic water introduced into the country rock and of circulating ground water penetrating the magma are unknown. It is possible that both types of fluids are simultaneously dominant in different portions of the magma chamber.

Such questions are being attacked through studies of the isotopic and chemical compositions of the hydrothermal fluids and the associated rock and silicate melts. Among the chemical and isotopic techniques being applied to this problem, the measurements of D/H and $^{18}O/^{16}O$ ratios have high priority. Meteoric ground waters in country rock always have distinctly lower ^{18}O contents than magmatic waters. In geographic sites at high latitudes or high elevation, D/H ratios of the meteoric-hydrothermal waters will also be much lower than the magmatic waters. These isotopic and chemical measurements could answer the question of how much (if any) magmatic water is present in circulating meteoric solutions at successive depths. This is important in understanding both heat transport and transport of various chemical species, including possible ore-forming constituents such as Pb, Cu, As, Au, Zn, and S.

Patterns of hydrothermal alteration. Studies of the patterns of hydrothermal alteration have proved to be a vital tool in mineral exploration, particularly in deposits of the porphyry copper type. A drill hole through hydrothermally altered wall rock of a magma chamber would provide an opportunity to study alteration products *in situ* over a wide but known range of temperatures, pressures, and chemical compositions. The results would add considerable precision to interpretations of alteration haloes in and around ore bodies.

Scientific Objectives of Drilling into an Active Magma Chamber

Petrological and chemical problems. In the past, information on magma bodies and associated wall rocks has come primarily from two sources: (1) studies of actual rocks in the field and laboratory, and (2) laboratory experiments on phase relationships of silicates and volatile constituents. Both types of studies suffer from serious limitations. In the field, we cannot study magmas at the time of crystallization, except for lava lakes as at Kilauea. The rocks formed at depth that we collect and study have passed through a complex sequence of postmagmatic subsolidus phase changes and reactions with meteoric and magmatic waters. Experimental studies are limited to a few components (usually 6)—far fewer than are found in natural systems. The experimenter must choose from a wide range of physical and chemical conditions, without knowing which of them are relevant to actual conditions in a magma chamber.

If samples, as well as physical data, could be obtained from magmas and rocks in contact with them, it would be possible to place field and laboratory observations under proper constraints and to sort out magmatic and postmagmatic reactions in natural rocks. A first step in this direction has been made by drilling through the crust of several recent Hawaiian lava lakes. These studies have provided information on the properties of basaltic lava, on the cooling processes of ponded flows, and on techniques of drilling and inserting probes into molten lava.

A drill that penetrates a magma chamber, if only for a few meters, provides exceedingly valuable information on the state of crystallization of the magma. Chilled samples from each centimeter of penetration can be obtained and examined for the following information: (1) bulk chemical composition, major elements and trace elements (including volatile elements); (2) chemical composition of individual phases; (3) abundance, size, and texture of phenocrysts; reaction relations between phenocrysts and liquid; (4) presence of xenoliths and xenocrysts; reaction relations between xenoliths and liquid.

Because magma samples would be obtained close to the magma–wall rock interface, measurable gradients in composition can be expected, even over a short distance of penetration. The samples collected, along with measurements of temperature, pressure, and oxygen fugacity, would give an accurate two-dimensional model capable of reproduction in the laboratory. If samples were obtained from two drill sites, a limited three-dimensional model could be constructed. The models would give information on the following:

1. Thermal balance, at the magma–wall rock interface, between latent heat of crystallization of growing phenocrysts and latent heat of solution of resorbing phenocrysts and xenoliths. Excess heat transferred to the wall rock is by far the largest source of geothermal energy, and the mechanism of transfer of this heat is largely unknown.

2. Chemical gradients in the magma and solid phases, if measured, could be used to calculate diffusion rates, especially of volatile and mobile elements. The direction of movement and chemical state of volatile elements found in ore-forming fluids (H, O, C, Cl, S, B, and F) are particularly significant. The chalcophile metals and the alkali metals, especially K, would be of particular interest. The degree of chemical transfer from the wall rocks into the magma is difficult to evaluate in any way other than by examining the dynamic situation at the actual magma contact.

3. Variations in growth patterns of phenocrysts would give significant information on crystal kinetics.

4. Samples from two drill holes, penetrating different parts of the same magma chamber, would give important information on differences in physical and chemical conditions at a particular instant. Variations in chemical conditions of single bodies of igneous rock are, of course, well documented from numerous field studies. However, it usually cannot be determined whether the variations formed simultaneously or separately. Again, the behavior of volatile and mobile elements would be of special interest.

5. Accurate information on crystal content, volatile content, density, viscosity, convective motion, oxygen fugacity, and chemical gradients of magmas would place important constraints on proposed mechanisms of magmatic differentiation such as crystal settling and volatile transfer. In the absence of accurate information, these have been debated inconclusively by petrologists for a century.

The objectives of drilling through wall rocks would vary greatly with the composition of wall rock. Permeable detrital sediments, carbonates and other chemically reactive rocks, and crystalline basement rocks would all behave in different ways.

In addition to measurements of temperature, pressure, and composition of rocks and gases, every effort should be made to obtain samples from the magma–wall rock interface. Because of the possible importance of short-range diffusion effects, it would be highly desirable to obtain a continuous core for about 5 m from the interface. For whatever distance that contact effects can be observed, wall rocks should be examined for the following: (1) changes in bulk chemistry; (2) mineralogical changes resulting from isochemical recrystallization or metasomatism; (3) variations in composition, pressure, and temperature of the pore fluid; (4) variations in isotopic composition due to exchange with magma and aqueous fluids; (5) variations in content of heavy metals resulting from introduction of or leaching by hot fluids.

The observations would throw light on a number of poorly understood geologic processes, among them:

1. The role of volatile transfer in magma–wall rock relations. By measuring concentrations of mobile elements and ambient temperatures and pressures in the magma, magmatic fluids, wall-rock pore fluids, and wall rocks, information will be gained on the roles of volatile transport and solid-state diffusion. The role of potassium is particularly important in view of the classic "granitization" controversy and the significance of potassic alteration associated with copper minerals in sulfide deposits.

2. The behavior of chalcophile metals. This is of particular significance to the study of ore deposits. It has never been resolved whether copper and other heavy metals of porphyry deposits were derived from magmas and carried to their present locations by magmatic fluids or leached from wall rocks and carried by meteoric waters toward a magma body which is undersaturated with respect to the volatile phases. Conceivably, both processes may operate at different levels of the same magma body. This is another reason for drilling two holes—one at the apex (more likely to be volatile saturated), the other at the flank (more likely to be unsaturated) of the magma chamber.

3. The mixing behavior of leads from habitats differing in uranium and thorium contents and isotopic compositions. This behavior has been a center of controversy in calibration of Pb/U dating techniques.

4. Calibration of geologic thermometers under natural conditions. Numerous geologic thermometers (fluid inclusions, inversions, phase changes, isotopic fractionation, loss of volatile elements and resetting of radioactive clocks, destruction of fission tracks, etc.) have been used. All of them need to be confirmed and calibrated under natural conditions.

5. Measurement of thermal gradients, thermal conductivity, and pore-fluid pressure gradients. Such measurements would permit studies of heat transfer from the magma to the wall rock.

6. Stability of hydrothermal alteration products. Zoning of hydrothermal minerals has been variously ascribed to successive pulses of altering fluids or to gradients in a single pulse. The actual minerals, fluids, and physical conditions encountered in a drill hole would be valuable for calibrating one of the most widely used techniques in prospecting for hydrothermal ore deposits.

Physical experiments in the magma chamber. Depending upon the viscosity of the magma and strength of the wall rocks, several physical experiments might provide critical information on the dynamics of a magma chamber and on its likely mode of emplacement.

1. Injection of chemical or isotopic tracers. Injected in the magma, tracers can be used to study both long- and short-range diffusion. If there is rapid convection in the magma, tracers would also provide data on the mass transfer and mixing by convection. Since it is possible that materials will migrate both inward and outward from the magma chamber, appropriate tracers should be released in the wall rocks as well as in the magma.

2. Release and tracing of active acoustical sources. Depending upon rates of convective motion, acoustical sources could be released in the magma to study its convective motion or its viscosity. Sources might be designed as pingers or as explosive charges. Neutrally buoyant sources would provide data on velocity and velocity gradients; sinking sources would provide data on viscosity.

3. Measurement of flow by deformation of drill hole. Flow in very high viscosity magmas or in plastic wall rocks could be studied directly by measurements of deformation of the drill hole or emplaced drill string. The viscosity profile could be measured by means of a penetrometer (with a hot tip, if necessary). Investigation of the fabric of recovered samples would be an important adjunct to these experiments.

4. Ultrasonic and high-frequency sound experiments. The abundance, distribution, and size of crystals in the magma as well as bulk properties of the magma could be investigated by *in situ* ultrasonics or by scattering and attenuation of very high frequency seismic waves.

Strategy and Site Selection

Although there are approximately 600 active volcanoes in the world and many more so-called dormant volcanoes, there are only about a half dozen fundamentally different types that can be distinguished by tectonic setting, the composition of the erupted materials, and mode of eruption. Of these, one of the most important types, from the standpoint of geothermal energy resources and hydrothermal mineralization, is the large caldera which produces voluminous rhyolitic flows and ash flows.

Most current geothermal exploration is in the United States near or at the sites of recent rhyolitic volcanism. Several of these sites may be located over an accessible magma chamber. The near-surface heat flow at each of these sites is very high, and some have active

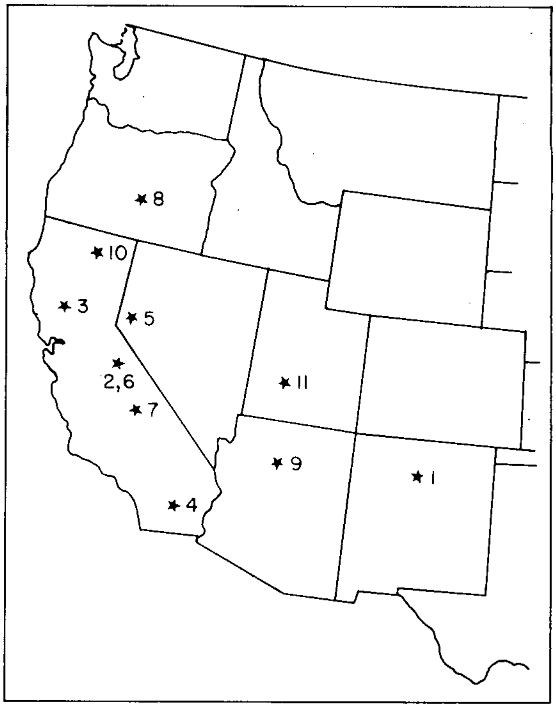

Figure B.1.1 Location of candidate sites for investigation of hydrothermal-magmatic systems. (1) Valles Caldera, New Mexico; (2) Long Valley, California; (3) The Geysers-Clear Lake area, California; (4) Salton Sea-Imperial Valley area, California; (5) Steamboat Springs, Nevada; (6) Mono Craters, California; (7) Coso Mountains, California; (8) Paulina-Newberry area, Oregon; (9) San Francisco Mountain, Arizona; (10) Medicine Lake, California; (11) Roosevelt Hot Springs, Utah.

natural geothermal fields. The sites that have already been drilled in search of exploitable geothermal energy include (Figure 3) Valles Caldera, New Mexico, near Los Alamos (may be too old); Long Valley, California, north of Bishop; The Geysers–Clear Lake area, California, north of San Francisco; Salton Sea–Imperial Valley area, California; Steamboat Springs, Nevada, south of Reno (may be too old).

Other sites of a similar nature, not as well explored, include Mono Craters, California, north of Bishop (no evident hydrothermal system); Coso Mountains, California, south of Bishop (probably very limited hydrothermal system); Paulina-Newberry area, Oregon; San Francisco Mountain, Arizona, near Flagstaff (no evident hydrothermal system); Medicine Lake, California; Roosevelt Hot Springs, Utah, northeast of Milford; Mt. Drum, Alaska (remote location).

The above sites constitute a promising list from which a single site can be selected after further reconnaissance investigations. Yellowstone, Mount Lassen, Crater Lake, and Katmai also are sites of potential interest, but their location in national parks and the accompanying environmental problems of drilling make them unlikely choices.

Reconnaissance studies and site selection. Reconnaissance and detailed studies of candidate sites should be directed at two goals: (1) determination of the existence of a magma chamber, its position and properties; and (2) working models for the thermal, physical, and chemical state of the magma chamber and the surrounding hydrothermal system. The best means of accomplishing the first goal is through geophysics. Young calderas and silicic rocks; local, unusually high near-surface temperature gradients; and high heat flows probably indicate the presence of magma at depth in several localities. However, the likelihood of convective transport of heat below the depth of measurement makes extrapolation of the thermal gradient to depth uncertain. Active seismic exploration together with other geophysical techniques can be used to determine the size, shape, and depth of a magma chamber, as has been demonstrated at Yellowstone National Park.

Geological studies, including completion of on-going detailed geologic mapping and thorough petrologic investigation should be carried out for the most promising candidate sites. These studies will be needed not only to interpret the history and model the present state of the magma chamber, but also to evaluate conditions likely to be encountered in drilling. A detailed knowledge of the geology of the site is critical for interpretation of recovered samples and other data obtained from deep drill holes.

It is reasonable to proceed with geophysical and geological reconnaissance at several candidate sites for about two years. At that time sufficient information should be available to make a choice of sites and to commit further intensive effort to selected sites. Much of this reconnaissance is under way in the present geothermal program, but the critical experiments to demonstrate the existence and depth of the magma chamber remain to be done at most sites. Enough information already is in hand to select a vapor-dominated geothermal system and to begin exploration of the deep hydrothermal zone.

Supporting research. In parallel with geophysical and geological investigations of candidate sites, supporting research activities should proceed. Small-scale field testing of drilling techniques, instrumentation, and sampling methods can be done in the basaltic Hawaiian lava lakes. Even though these small magma bodies are compositionally different from rhyolites of caldera complexes, they are readily accessible and offer the advantage of good working scale and support. Alae is a lava lake with a thin crust; Kilauea Iki has a stable and thick crust (about 45 meters) beneath which is a molten lava layer 30–40 meters thick. Intensive laboratory research on measurements of the physical and thermochemical properties of silicate melts and vapor-bearing systems should proceed at the same time. Special effort must be made to devise methods for evaluating data from initial high temperature and pressure measurements where the drill hole itself will have strongly perturbed the original conditions.

Evolution of the research effort. The research effort should evolve over five to seven years, extending from the initial geological and geophysical reconnaissance of several candidate sites to the final stage of drilling into the vicinity of a magma chamber. A reasonable sequence of tasks is the following, some overlapping in time:

1. Reconnaissance geophysics at three to four candidate sites—including seismology, heat flow, gravity, magnetotelluric and, possibly, resistivity methods—designed to demonstrate the existence of magma or partially molten rock at depth and to define as closely as possible the margin of the magma chamber. This work is currently under way in existing geothermal programs.

2. Geologic mapping and petrologic investigations of candidate sites, as well as analogous sites at deeper erosion levels, to generate working models. This work is also in progress.

3. Exploratory shallow to moderate-depth drilling at the most promising sites, including drilling with instrumented holes to obtain samples and data for investigation of the hydrothermal systems.

4. Tests in the Hawaiian lava lakes for engineering research and development and scientific purposes.

5. Selection of a prime site and detailed geophysical, geological and petrological investigations, including a supporting array of shallow and intermediate-depth holes for instrumentation.

6. Finally, drilling and experiments near or within a magma chamber.

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