LA-8550-OBES

(2)

Dr. 2231

R-1427

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Continental Scientific Drilling Program

Thermal Regimes:

Comparative Site Assessment Geology of

Five Magma-Hydrothermal Systems

University of California

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This work was supported by the US Department
of Energy, Office of Basic Energy Sciences.

This report is part of the DOE/OBES Geo-
sciences Continental Scientific Drilling
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LA-8550-OBES

UC-66b

Issued: October 1980

Continental Scientific Drilling Program

Thermal Regimes:

Comparative Site Assessment Geology of

Five Magma-Hydrothermal Systems

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FOREWORD

The US Geodynamics Committee (1979) in their booklet "Continental Scientific Drilling Program" (CSDP) stressed the need for deep continental drilling of magma-hydrothermal systems. As a first step toward picking a target for such a venture, the Department of Energy, Office of Basic Energy Sciences (OBES) has funded four national laboratories to participate cooperatively in a comparative assessment of five significant magma-hydrothermal systems of the USA. This report summarizes the geology of five high-grade magma-hydrothermal systems and suggests target areas within each system for a deep borehole. Companion volumes on the geophysics and geochemistry of each system are being compiled by P. Kasameyer, Lawrence Livermore Laboratory (LLL) and A. White, Lawrence Berkeley Laboratory (LBL), respectively with the help of their contributors. A fourth volume on energy transport of magma-hydrothermal systems has been written by H. Hardee, Sandia National Laboratory (SNL). An Executive Summary of these combined efforts will be published by W. Luth and H. Hardee, SNL.

CONTINENTAL SCIENTIFIC DRILLING PROGRAM THERMAL REGIMES:
COMPARATIVE SITE ASSESSMENT
GEOLOGY OF FIVE MAGMA-HYDROTHERMAL SYSTEMS

Editors

Fraser Goff and Aaron C. Waters

ABSTRACT

This volume reviews the geology and salient aspects of geophysics and hydrogeochemistry of five high-grade geothermal systems in the USA. On the basis of this information, a target location is suggested for a deep (5- to 8-km) borehole that will maximize the amount of scientific information to be learned at each of the five geothermal areas.

No priority levels are recommended, but from the nature of the data assembled, reviewers should have little difficulty in reducing the five candidates to two or three.

INTRODUCTION

Geology of the five magma-hydrothermal systems under investigation (Fig. 1) presents many similarities and contrasts. A few generalizations that emphasize similarities are easily listed: 1) all five systems are located in portions of the western USA where average heat flow is ≥ 2 HFU, 2) all systems are associated with silicic volcanism less than 1 Myr old, 3) all systems occur in an extensional tectonic environment where deep-seated faults and fractures have allowed basaltic magma to rise and provide heat to activate silicic melts, 4) all systems possess currently active hot springs and other thermal phenomena denoting elevated temperatures in the near surface, and 5) all are high-grade geothermal systems that are being systematically explored by private corporations for energy resources.

For contrasts, first let us examine differences in size. Table I compares estimated quantities of thermal energy stored within each system with the thermal energy of associated hydrothermal systems and with approximate volumes of associated volcanic rocks. (Note: Valles Caldera is the most

Fig. 1.
Map of western USA showing locations of five magma-hydrothermal systems of this review.

significant magma-hydrothermal system of the Rio Grande rift. Calculations for the entire rift are not available.) We note immediately from the table that the estimated total of stored heat is roughly proportional to volume of silicic volcanics generated within the system. However, there is no correlation of total size with size of associated hydrothermal systems; the largest hydrothermal system, Salton Trough, has formed near the smallest silicic volcanic system, and shows no clear genetic association with the volcanics.

A second important difference is volcanic style (Table II). The two largest systems in terms of total heat, Valles Caldera and Long Valley, are both silicic calderas that have erupted copious ash-flow tuffs. Their most recent episodes of volcanism are distinctly rhyolitic. On the other hand, the remaining systems have erupted primarily domes and flows. Volcanism at the smaller systems follows no distinct pattern except that silicic rocks seem to dominate. The Clear Lake Volcanics span the entire range basalt through

TABLE I

TOTAL ESTIMATED THERMAL ENERGY OF FIVE MAGMA-HYDROTHERMAL SYSTEMS
(TO A DEPTH OF 10 km) COMPARED WITH THERMAL ENERGY OF ASSOCIATED
HYDROTHERMAL SYSTEMS AND VOLUMES OF ASSOCIATED SILICIC VOLCANICS
(data from USGS Circs. 726 and 790, 1975; 1979)

	Thermal Energy in Magma-Hydro- Thermal System 10^{18}J	Thermal Energy in Associated Hydrothermal Systems, 10^{18}J	Volume of Asso- ciated Silicic volcanics, mostly $\leq 1\text{ Myr}$, km^3
Clear Lake region, CA	3610	100 ¹	75
Long Valley Caldera, CA	5780	78	≈ 200
Roosevelt Hot Spgs., UT	710	32	15
Salton Trough, CA ²	480	230 ²	< 2
Valles Caldera, NM ³	8425	87	≈ 500

¹Estimate for The Geysers only, does not include Calistoga, Sulphur Bank Mine, Wilbur Springs, and small systems near Clear Lake.

²Does not include Cerro Prieto, Mexico.

³No data available for entire Rio Grande rift.

rhyolite with dacite most voluminous. Roosevelt Hot Springs volcanism is bimodal basalt-rhyolite. Salton Trough volcanism is represented by only five small eruptions, all dacite-rhyolite.

A third interesting comparison is tectonic setting. Three of the magma-hydrothermal systems occur within or adjacent to tectonic provinces of extreme normal block faulting: the Basin and Range and Rio Grande rift provinces. The two caldera systems have developed in these zones. The two remaining systems have formed on top of or adjacent to the San Andreas transform zone. Details of tectonic style vary at each location, but extensional tectonics are common to all.

A fourth comparison worth noting is differences in hydrothermal systems. All systems have hot water-dominated reservoirs, but the reservoirs vary considerably in size. The two calderas possess hot water-dominated reservoirs of only modest size and small zones of fumaroles. The remainder of the Rio Grande rift contains a multitude of small hot water reservoirs of diverse composition.

TABLE II

COMPARATIVE INFORMATION ON VOLCANIC STYLES, TECTONIC SETTINGS, AND HYDROTHERMAL RESERVOIRS
OF FIVE MAGMA-HYDROTHERMAL SYSTEMS

	Volcanic Style	Tectonic Setting	Hydrothermal Systems
Clear Lake region, CA	Silicic volcanic field, mostly dacite-basalt; no ash-flow tuffs; age: 2 - 0.01 Myr	Adjacent (east) of San Andreas transform zone; located in early Tertiary subduction zone.	Large vapor-dominated reservoir at The Geysers, $T = 240^{\circ}\text{C}$; several distinct hot water reservoirs to east, $T = <200^{\circ}\text{C}$; many fumarole areas and mercury deposits.
Long Valley Caldera, CA	Silicic caldera with copious ash-flow tuffs and rhyodacite domes; age: 0.7 - <0.01 Myr.	West margin of Basin and Range province adjacent to east Sierra Nevada escarpment.	Several small hot water reservoirs $T = \leq 180^{\circ}\text{C}$; one fumarole area.
Roosevelt Hot Sprgs., UT	Bimodal basalt-rhyolite suite; some small ash-flow tuffs; age: 0.8 - <0.01	East margin of Basin and Range province; adjacent to NW Colorado Plateau.	Moderate-sized hot water reservoir, $T = 260^{\circ}\text{C}$.
Salton Trough, CA	Four rhyolite and one dacite domes; age: <0.1 Myr.	Overlies transform zone associated with East Pacific Rise and San Andreas fault system.	Many hot water reservoirs, $T = \leq 350^{\circ}\text{C}$; one fumarole area.
Valles Caldera, NM	Silicic caldera with copious ash-flow tuffs and rhyodacite domes; age: 1.4 - 0.1 Myr.	Junction of Rio Grande rift and Jemez volcanic lineament at SE margin of Colorado Plateau.	Moderate-sized hot water reservoir, $T = 260^{\circ}\text{C}$; contains small vapor-dominated zone; two fumarole areas.

Salton Trough contains several hot water-dominated reservoirs displaying wide ranges in volume, temperature, and chemical composition. The Clear Lake region holds an extensive vapor-dominated reservoir at The Geysers and several small hot water reservoirs to the east. Extensive fumarolic activity and young mercury deposits abound in the Clear Lake region.

The Continental Scientific Drilling Program (CSDP) affords a unique opportunity to stimulate extremely valuable research on magma-hydrothermal systems. Although detailed geologic mapping of the five systems is largely complete (Rio Grande rift is a major exception), many questions remain to be answered regarding the petrology, geochemistry, age, distribution, volume, hydrothermal sealing, and general evolution of the magmatic systems. More needs to be understood on age, evolution, and mechanisms of tectonic environments. Perhaps the most significant contributions could be made toward understanding the relationships of hydrothermal systems to associated magmatic systems. What are the controls of recharge, circulation, permeability, volume, temperature, and composition within hydrothermal systems? Why are some systems so extensive and others so small, even though abundant heat may be available to all? How do vapor-dominated systems form and evolve? A carefully chosen exploration drill hole (5-8 km deep) could help in solving many of these problems.

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GEOLOGY OF THE GEYSERS-CLEAR LAKE
GEOTHERMAL REGIME, NORTHERN CALIFORNIA

by

Fraser Goff

ABSTRACT

The Geysers-Clear Lake region contains two large geothermal provinces: a vapor-dominated province in The Geysers area and a hot water-dominated province to the east. The heat source supplying the geothermal systems is present or former silicic magma reservoirs in the shallow crust that also sourced the Clear Lake Volcanics of mostly Quaternary age. Geothermal reservoirs of several kinds are contained within a basement of fractured Mesozoic marine sediments and associated rocks of the Franciscan assemblage and Great Valley sequence. The basement rocks are structurally complex because of early Tertiary thrusting resulting from subduction, and late Tertiary high-angle faulting caused by movement along the San Andreas transform zone. Geophysical investigations support the concept of a present magma reservoir(s) and define the active tectonics within the region. Geochemical studies of thermal waters subdivide the two geothermal provinces and help unravel some of the subsurface basement geology. Associated investigations pertaining to local and regional geology are discussed, and unresolved problems concerning the geothermal systems are listed at the end of this review.

I. INTRODUCTION

The Geysers-Clear Lake region of California, 150 km north of San Francisco, (Fig. 2) is now the largest commercially exploited geothermal regime in the world. Approximately 800 MWe are now generated from The Geysers vapor-dominated system and 2000 MWe are expected in the future. Unexploited hot water-dominated geothermal reservoirs of unknown temperature and volume lie east, north, and south of The Geysers. The Clear Lake Volcanics overlie at least 100 km² of relatively impermeable Mesozoic basement that may be exploitable by hot dry rock geothermal techniques. The Clear Lake region is renowned for the variety of natural waters that have brought tourists to local spas and resorts for over 100 years.

Fig. 2.

Location map of The Geysers geothermal area and late Tertiary and Quaternary volcanic rocks; McLaughlin and Stanley (1976). The V pattern indicates location of Clear Lake Volcanics; line pattern, Sonoma Volcanics. White areas are predominantly Mesozoic basement rocks.

All evidence indicates that the heat source creating the geothermal system is past or present silicic magma reservoirs that have erupted in the Plio-Pleistocene Clear Lake Volcanics. The distribution of volcanic rocks correlates with a large regional negative gravity anomaly, suggesting low-density material in the shallow crust. Hot springs, fumaroles, and young mercury deposits abound throughout the region. Approximately 10 deep exploration wells drilled through the Clear Lake Volcanics have revealed temperatures of roughly 200°C at depths as shallow as 2000 m. The temperature of The Geysers vapor-dominated reservoir is about 240°C to a depth of nearly 4000 m.

Reservoir rocks for thermal fluids of all types are fractured graywackes and other marine rocks of the Franciscan assemblage and the Great Valley sequence. These two major geologic units make up the bulk of the California Coast Ranges and provide a structurally complex basement geology because of the combined effects of early Tertiary subduction and late Tertiary San Andreas-style faulting.

The object of this review is to provide an overview of The Geysers-Clear Lake thermal regime and to discuss salient aspects of geology within this region. Brief mention will be made of geophysical and hydrogeological data specifically relevant to the geothermal resources. The review summarizes research published through 1980, contributed mainly by the US Geological Survey (USGS) geothermal program, particularly by R. J. McLaughlin, B. Carter Hearn, Jr., and various other co-workers on the USGS project.

A useful paper stressing geologic and environmental restrictions to geothermal development is by Crow (1979). A comprehensive USGS professional paper edited by J. M. Donnelly and R. J. McLaughlin will be published in 1981 concerning a variety of subjects in The Geysers-Clear Lake region. Researchers at the Los Alamos Scientific Laboratory, New Mexico, are about to embark on an assessment of the Clear Lake region for hot dry rock geothermal potential. Active geothermal exploration programs are being conducted by at least 10 private companies.

II. GEOLOGY

The rocks of The Geysers-Clear Lake region consist of structurally complex marine sediments and ophiolite of the Franciscan assemblage and Great Valley sequence, overlain and intruded by the Clear Lake Volcanics, which comprise a young silicic volcanic field. A relatively large structural basin east of Clear Lake holds most of the Cache Formation, a Late Tertiary fluvial to lacustrine unit. Clear Lake itself lies in a currently evolving structural basin that has been accumulating sediments for the last 135 000 years or more.

Franciscan and coeval Great Valley rocks (Jurassic to Eocene) were brought into contact by the undulating, regional Coast Range thrust. This thrust zone represents part of the trace of an eastward-dipping early Tertiary subduction zone along which the eastern Great Valley sequence has been piled upon the western Franciscan assemblage. The structural configuration due to

subduction was modified in the late Tertiary by a subparallel set of right-lateral strike-slip faults related to the San Andreas fault system (Fig. 3). The Clear Lake Volcanics, which are mostly less than 1 Myr in age, document considerable offset by two of these strike-slip zones.

Regional topography, consisting primarily of northwest-trending valleys and ridges, is controlled by strike-slip faulting. The major exception to this rule is the highland occupied by the Clear Lake Volcanics, which displays many domes and small basins.

Mesozoic Basement Complex: Lithology. The Franciscan assemblage (Fig. 4) is an eugeosynclinal accumulation of graywacke, shale, chert, and basalt (now greenstone) with subordinate amounts of conglomerate and limestone (Bailey et al., 1964; 1970; McLaughlin, 1977). Franciscan rocks are metamorphosed mainly

Fig. 3.

Map showing major right-lateral strike-slip fault zones of the San Andreas system in relation to The Geysers, the Clear Lake Volcanic field, and the Cache Formation. Dashed line outlines the Geysers steam field.

Fig. 4.
Generalized geologic map of The Geysers steam field and vicinity; McLaughlin (1977).

to zeolite facies, but blueschist facies rocks are not uncommon. The higher degrees of metamorphism presumably occurred during subduction episodes in the Cretaceous and early Tertiary periods (Hsu, 1968). In general, degree of metamorphism increases with proximity to the Coast Range thrust (Bailey et al., 1970). Serpentinities (metamorphosed peridotite and dunite) are interpreted to come from the bottom of the overlying Great Valley sequence, and are thrust over and into the Franciscan assemblage (McLaughlin and Stanley, 1976). A curious unit of metamorphosed serpentinite (antigorite-talc-actinolite schist) has been thrust into the Franciscan within The Geysers area and locally forms an impermeable cap rock for steam (McLaughlin, 1977).

The Franciscan is characterized by internal units with chaotic and/or discontinuous structures. These may be hectares to many kilometers in dimension. Such chaotic but mappable units are best grouped as melange, in which competent blocks of graywacke, greenstone, blueschist, and eclogite sit randomly in a friable matrix of sheared broken graywacke (Hsu, 1968; Bailey et al., 1964; 1970; Fox, 1976; McLaughlin, 1977).

The Great Valley sequence is a miogeosynclinal accumulation that consists of flysch-like units of graywacke, shale, and conglomerate overlying a basal ophiolite complex (Swe and Dickinson, 1970; McLaughlin and Stanley, 1976). The ophiolite, which represents ancient oceanic crust, is extremely variable in thickness and consists mostly of serpentinite. However, within the Clear Lake region, exposures of ophiolite may contain gabbro, diabase dikes and breccias, pillow-basalt, and chert. Great Valley rocks are metamorphosed only to zeolite facies because they occupied the upper plate of the Coast Range thrust during subduction.

Structural Relation between Franciscan and Great Valley Rocks. Plate-tectonic and subduction zone theories have greatly aided in interpretation and mapping of the complex geology in the Coast Ranges of California. The deformed ophiolite sheet, which forms the base of the upper plate of the Coast Range thrust, represents Jurassic oceanic crust that may have formed the floor of an arc-trench gap. This gap was filled with strata of the Great Valley sequence from sources to the east (Dickinson, 1970). West of Great Valley sedimentation, the Franciscan assemblage, including oceanic basalts from a spreading ridge far to the west plus some terrigenous and pelagic sediments, accumulated in an eastward-dipping subduction zone and associated trench (Hsu, 1968).

Subduction of these Franciscan rocks caused them to be shingled into an eastward-dipping series of imbricate thrust slabs beneath the oceanic crust and overlying sedimentary rocks of the Great Valley sequence. The result is that previously subducted (older) Franciscan units accrete to the hanging wall of the subduction zone and are thrust over younger Franciscan units to the west.

This relatively simple model has many local anomalies. In places, Great Valley rocks are thrust into and beneath ophiolite and Franciscan rocks (Wagner, 1977; Suppe, 1977, 1979). Suppe (1979) has suggested that a somewhat younger post-subduction thrusting event is responsible for much of the east-west crustal shortening seen in the Coast Ranges. Regardless of interpretation, Franciscan rocks are generally much more deformed and metamorphosed than Great Valley rocks. Because of lithologic similarities, formerly unrecognized exposures of Great Valley sequence continue to be found as isolated klippe (Berkland, 1973) and as faulted slabs (Suppe, 1977) within areas of Franciscan rocks.

During the last few million years, changes in the relative motions between the North American and Pacific plates due to passage of the Mendicino triple junction, terminated subduction and initiated strike-slip motion in the Clear Lake region (McLaughlin, 1977; Dickinson and Snyder, 1979). Many older thrust faults were reactivated as strike-slip faults, producing complex relationships. Such reactivation is particularly obvious along the Collayomi fault zone, which is not only a major right-lateral fault but also a major exposure of the Coast Range thrust.

Age Relations. Age determinations in both Franciscan and Great Valley rocks have been difficult to obtain due to a paucity of fossils. Within the Franciscan, this difficulty is enhanced by imbricate thrusts that place older units structurally above younger units. Several recent radiolarian ages determined by E. A. Passagno in The Geysers area place the age of structurally high Franciscan units at late Jurassic to early Cretaceous (McLaughlin and Stanley, 1976). Structurally lower Franciscan units to the west are known to be as young as Eocene (Blake and Jones, 1974).

Radiolarian ages from cherts both above and below the Coast Range thrust south of Boggs Mountain (in Great Valley and Franciscan rocks, respectively, Fig. 4) prove that the lower Great Valley sequence (Knoxville Formation) of Jurassic age is older than a slice of Franciscan assemblage thrust immediately beneath it (McLaughlin and Passagno, 1978).

Cache Formation: An irregular structural basin east of Clear Lake is filled with predominately fluvial deposits of silt, sand, and gravel of the Cache Formation (Fig. 3). The Cache is composed mostly of debris shed from surrounding Franciscan and Great Valley rocks. Stratigraphic thickness according to Brice (1953) exceeds 1600 m. Rare outcrops of basaltic lavas of the Clear Lake Volcanics (age about 1.3-1.9 Myr) occur within the Cache Formation along the Wilson Valley fault zone (Fig. 3) at relatively high stratigraphic levels, suggesting that most of the Cache is Plio-Pliocene in age (Rymer, 1978; Donnelly, 1977).

Exposures of Cache Formation near Clear Lake are intimately interbedded with and derived from the Clear Lake Volcanics. Lithologically, these outcrops contain more lacustrine deposits, volcanoclastic sands and silts, and diatomites, and have an age range from about 1.6 to <0.05 Myr (Rymer, 1978; Donnelly et al., 1977). Because of these distinct variations Rymer (1978) has subdivided the Cache Formation into three members.

Clear Lake Volcanics: Lithology, Volume, Eruptive Style. The Clear Lake Volcanics are a predominately silicic volcanic field consisting of basaltic through rhyolitic rocks that erupted as domes, flows, and minor pyroclastics (Fig. 5). The eruptive sequence is structurally and chronologically complex although, in general, the age of volcanism decreases northward and the volume of silicic rocks has increased with youth of the field (Anderson, 1936; Brice, 1953; Hearn et al., 1976a and b; in press).

Volumetrically, dacite and rhyolite comprise roughly 50 km^3 whereas basalt and andesite constitute another 35 km^2 (Donnelly, 1977). Approximately half the volume of the Clear Lake Volcanics resides in the composite dome of Mt. Konocti, which is built mostly of dacite less than 0.4 Myr old.

Most Clear Lake basalts are really basaltic andesites having phenocrysts of olivine and resorbed quartz grains of controversial origin. Andesites generally contain phenocrysts of plagioclase, ortho- and clinopyroxene. Dacites, which occur as highly porphyritic and sparsely porphyritic types, generally possess phenocrysts of plagioclase, ortho- and clinopyroxene, hornblende, biotite, and quartz. Large sanidine megacrysts are found in most highly porphyritic types. Crystal-rich rhyolites carry biotite phenocrysts and occur as domes, while crystal-poor rhyolites carry plagioclase and orthopyroxene phenocrysts and outcrop as extensive flows.

Fig. 5.

Generalized geologic map of Clear Lake volcanic field, showing K/Ar ages and magnetic polarities. Lake and alluvial deposits are shown only near Clear Lake. Order of volcanic units in explanation is not sequence of eruption. Lateral extent of cinder cones shown where associated with flows. Contacts shown within a single rock type are between flows of different age and/or magnetic polarity. Faults dashed where inferred, dotted where concealed. Geology in part modified from Brice (1953), Lake County Flood control and Water Conservation District (1967), and Sims and Rymer (1976). Abbreviations of geographic names (+ denotes location): B = Boggs Mountain, C = Cobb Mountain, H = Mount Hannah, K = Mount Konocti, S = Seigler Mountain, BP = Buckingham Peak, KB = Konocti Bay, CP = Caldwell Pines, CV = Cobb Valley, SB = Sulphur Bank, BL = Borax lake, LB = Little Borax Lake, TL = Thurston Lake, CH = Clearlake Highlands, KV = Kelseyville, LL = Lower Lake, LP = Lakeport, M = Middletown; Hearn et al., 1976.

One crystal-poor rhyolite has erupted as an extensive deposit of air-fall pyroclastics that provide an excellent stratigraphic marker on the southern side of the volcanic pile (Rhyolite of Bonanza Springs). No ash-flow tuffs (ignimbrites) have erupted in the Clear Lake Volcanics in contrast to other large magma-hydrothermal systems such as Yellowstone, Wyoming, and Valles Caldera, New Mexico. Ash-flow tuffs as young as 2.9 Myr are found in the Sonoma volcanics near Calistoga, south of Clear Lake (Makinen, 1972).

Extensive potassium-argon age determinations on whole-rock and mineral separates by Donnelly (1977) yield an age range of 2.04-0.03 Myr for the Clear Lake Volcanics. The dates together with detailed geologic mapping and magnetic polarity determinations (Hearn et al., 1976b; Makinen et al., 1978) have produced extremely good stratigraphic control.

Local eruptive sequences have been described in detail by Donnelly (1977). Rhyolite ages range from 2.04 Myr in the south of the field to 0.088 Myr in the north. The greater volume of basaltic eruptions, which lie southeast of the main volcanic pile, was erupted before 1.3 Myr ago. Extensive silicic eruptions began with the sequence at Cobb Mountain adjacent to The Geysers at 1.14 Myr ago. Most silicic volcanism ceased with formation of the top of Mt. Konocti 0.3 Myr ago. The most recent eruptions in the Clear Lake sequence have been mafic cones, flows, and maar deposits as young as 10 000 years old (Donnelly, 1977; Sims and Rymer, 1975) which are found within, adjacent to, and north of Clear Lake.

Structures of Intravolcanic Age. Two major strike-slip faults with apparent right-lateral components cut the Clear Lake volcanic field: The Collayomi and Konocti Bay fault zones (Figs. 3 and 5). Offset volcanic contacts along the Collayomi fault zone in units less than 0.5 Myr old suggests a continuous deformation rate of about 1 mm/yr (Hearn et al., 1976a). The major displacements along individual fault strands within these zones are generally normal, however, a particularly instructive example of reverse faulting along the Collayomi fault zone can be seen west of Mt. Hannah (stop 9 of Donnelly et al., 1977) where altered serpentinites have been thrust over Quaternary gravels containing volcanic cobbles derived from Cobb Mountain (age 1.14 to $\approx$ 1.0 Myr).

Approximate locations of earthquake epicenters as great as 4.6 magnitude suggest that movement on the Collayomi fault zone is currently occurring (Hamilton and Muffler, 1972; Chapman, 1975; Hearn et al., 1976a). Some locally

felt earthquakes have been reported by residents who live on or adjacent to the Konocti Bay fault zone, and Bufe and Lester (1975) have discussed strike-slip fault plane solutions for seismic events along this fault zone.

A prominent set of north and northeast-trending faults occurs between the major strike-slip fault zones. These faults are mapped with normal or reverse displacements, but one at Sulphur Mound Mine (south of Mt. Konocti, Figs. 3 and 5) displays possible evidence of left-lateral movement (B.C. Hearn, USGS, personal communication, 1977). If so, the north and northeast-trending faults are probably tensional structures responding to stresses generated between parallel northwest-trending strike-slip fault zones (Hearn et al., in press). Vertical offsets along these north-trending faults could also result from various episodes of doming and uplift due to shallow intrusion of silicic magma (Hearn et al., in press).

There is some evidence that the youngest Clear Lake basaltic magmas have ascended along deep-seated north-trending fault or fracture systems. Two belts of relatively young basaltic vents less than 0.4 Myr are aligned north-south, straddling the east and west sides of the volcanic field (Fig. 5). The vents in each belt become younger to the north as is typical of Clear Lake volcanism.

Relation to Coast Range Volcanism. The Clear Lake Volcanics are the youngest of a series of volcanic fields that overlie or are adjacent to the San Andreas transform zone. Because each volcanic field is progressively younger to the north, Hearn et al., (1978) suggested that these volcanic fields are surface expressions of a mantle hot spot underlying the North American Plate (east side of San Andreas transform). On the other hand, McLaughlin (1977) and Dickinson and Snyder (1979) correlate the northward progression of volcanism to northward migration of the Mendocino triple junction in California. Passage of the triple junction causes cessation of subduction and commencement of extension. Extensional tectonics, with the deep-seated faults and fractures that ensue provides necessary conduits for ascent of basaltic magma from the mantle.

Quaternary Sediments: Big Valley on the northwest side of the Clear Lake Volcanics is filled with Quaternary sand, gravel, and silt equivalent to those now deposited in adjacent Clear Lake. Sims and Rymer (1975) and Adam and Sims (1976) have examined cores and pollen taken throughout Clear Lake

and have obtained ages from pollen records, ^{14}C determinations on peats, and sedimentation rates. They conclude that Clear Lake has been continuously in existence for the last 135 000 years. Mapped faults along the eastern side of Clear Lake (Sims and Rymes, 1976) suggest that the basin has been downdropped primarily along northwest-trending faults.

Due to the steep terrain and the large amount of melange, landslides comprise nearly 40% of outcrop in The Geysers area (McLaughlin, 1978). Large landslides or pseudo-landslide complexes occur in the Clear Lake Volcanics west of Mt. Konocti (Hearn et al., 1976b) and south of Cobb Mountain (Goff and McLaughlin, 1976). Landslides have extreme environmental significance to geothermal development (Crow, 1979) because of their detrimental effects on geothermal wells and power plants.

III. STRUCTURAL CONTROL OF GEOTHERMAL RESOURCES

The Geysers: Steam from the Geysers vapor-dominated system is produced from fracture zones in Franciscan graywacke. Imbricate thrusting and ubiquitous presence of impermeable units such as greenstones, argillites and serpentinites insure that traps for steam are present at many structural levels (McLaughlin and Stanley, 1976; McLaughlin, 1977). Three structural units have been distinguished in The Geysers area by McLaughlin (1977). Unit 1 is the lowest structural unit and is composed of weakly metamorphosed graywacke. Unit 2 rocks (overlying unit 1) consist of slabs of largely impermeable lithologies having more obvious metamorphic texture and locally including lawsonite. Rocks of the highest structural unit (unit 3) are mostly reconstituted by metamorphism into a mineral assemblage that may contain quartz $\pm$ phengite $\pm$ lawsonite $\pm$ albite $\pm$ jadeite $\pm$ glaucophane $\pm$ pumpellyite. This sequence of structural units is repeated by imbricate thrusting and more recent normal faulting (see Figs. 4 and 6) as young as 750 years (McLaughlin and Stanley, 1976).

McLaughlin and Stanley (1976) conclude that critical parameters for the economic concentrations of steam are: 1) the presence of channelways (faults and fractures) that allow percolation of meteoric water to depth, 2) the presence of favorable structural traps, 3) a potent heat source. The idealized model of the vapor-dominated zone imitates those proposed by White et al., (1971) and Muffler and White (1972). The model states that steam evolves from

Fig. 6.

Structural model for The Geysers-Clear Lake geothermal regime. Cross-section through The Geysers-Clear Lake region, from the Maacama fault zone on the southwest, to Mount Konocti on the northeast, depicting structural elements of The Geysers-Clear Lake geothermal system; McLaughlin (1977).

a very deep boiling brine. However, this brine has never been discovered by deep drilling even to depths over 3700 m. The nature of the potent heat source is also controversial. If we assume that silicic magma is the source, this magma occurs many kilometers south of the main gravity anomaly and defies the northward trend of decreasing age observed in Clear Lake volcanic rocks (see Figs. 6 and 7). Dikes and sills resembling the porphyritic volcanics of Cobb Mountain have been drilled in The Geysers steam field (Schriener and Suemnicht, 1980), but they represent an early phase of silicic magmatism (≈ 1 Myr ago).

Clear Lake Volcanic Field: The detailed geology beneath the Clear Lake Volcanics is highly speculative (e.g., Fig. 6). Great Valley rocks are

Fig. 7.

Residual Bouguer gravity of The Geysers-Clear Lake area, from Isherwood (1976), reduced at 2.67 gm/cm^3 ; 2 milligal contour interval. The Clear Lake Volcanics are shown with a V-pattern. The Collayomi fault zone divides the major gravity low into northeast and southwest lobes, and the Mercuryville fault zone bounds the gravity anomaly on the southwest side of The Geysers steam field; McLaughlin (1977).

exposed beneath the volcanics on the south and east sides of the field. Correlations between electrical resistivity lows, relatively chloride-rich thermal waters and exposed Great Valley rocks (Fig. 8) can be used to predict the concealed extent of the Great Valley sequence beneath the Clear Lake volcanic field (Goff et al., 1977). Deep exploration wells drilled through the Clear

Fig. 8.

Outline of Clear Lake volcanic field with resistivity contours (Stanley and others, 1973) and two patterns indicating the two major types of bedrock under the volcanic field. Heavy lines are major fault traces; figure from Goff et al. (1977).

Lake volcanics have encountered graywackes, argillite, greenstone, and serpentinites some of which are interpreted to be Franciscan. Serpentinites are known to exist beneath Mt. Konocti and the adjacent Konocti Bay fault zone because of 1) serpentine fragments in younger mafic ashes, 2) extremely high magnesium concentrations in thermal waters (Goff et al., 1976) and 3) linear positive magnetic anomalies (Isherwood, 1976; Goff et al., 1977). Unfortunately, Clear Lake and Big Valley on the east and north sides of the volcanic

field, hide Mesozoic basement rocks, but the closest exposures on those sides are Franciscan. A general distribution of basement rocks beneath the Clear Lake volcanics is shown in Fig. 8, but the structure is presumably complex as it is elsewhere in the Coast Ranges.

Exploratory drilling for hot-water has been largely unsuccessful except at known hydrothermal systems like Sulphur Bank Mine, because the basement rocks, although hot, are impermeable. The only large water entry known beneath the main volcanic field was struck recently at Sulphur Mound Mine in a major northeast-trending fault zone. It may be that economic reservoirs of hot-water will only be found where young faulting has enhanced permeability. All hot springs emerge along mapped faults.

IV. GEOPHYSICS

A rather complete suite of regional geophysical investigations have been conducted in The Geysers-Clear Lake region to explore the excellent geothermal potential. The major exception is thermal gradient and heat-flow information that has been obtained by private companies for exploration purposes and, thus, kept proprietary. More complete discussions of geophysics are presented in the report by Kasamayer.

Regional gravity data gathered by Chapman (1975) and Isherwood (1976) show that a circular negative gravity anomaly of 25 mgal overlies the Clear Lake Volcanics at Mt. Hannah (Fig. 7). This anomaly was interpreted to be caused by a possible silicic magma reservoir lying at depths of 7-10 km beneath the volcanic field. Teleseismic P-wave delays of 1 s or more measured by Iyer and Hitchcock (1975) suggest that attenuation of P-waves is being caused by hot plastic to partially molten material at depth. Because no magnetic high is associated with the gravity low of Mt. Hannah, Isherwood theorized that the heat source at depth may still be above its curie point, approximately 550°C. All these interpretations strongly indicate the existence of magma at depth.

The gravity data also show a smaller gravity low overlying The Geysers steam field (Fig. 7) but Isherwood (1977) believes this is due (at least in part) to the presence of steam in the near surface. Regional magnetic data reveal linear northwest trending positive anomalies that overlie exposed or probably buried serpentinites (Isherwood, 1976). Electrical resistivity data presented by Stanley et al. (1973) indicate a 3-ohm-m resistivity low centered in the Mt. Hannah area. This, in part, suggests the existence of warm and/or

saline fluid at depth, but resistivity lows have also been correlated with the presence of Great Valley sequence rocks (Stanley et al., 1973; Goff et al., 1977).

Bufe and Lester (1975) and Hamilton and Muffler (1972) have studied seismicity both regionally and at The Geysers. Abundant shallow seismic events at The Geysers have been correlated with withdrawal of fluid from the reservoir, and leveling data by Lofgren (1978) indicates subsidence occurring. Epicenters of regional events tend to correlate with mapped strike-slip fault zones, and fault plane solutions indicate strike-slip motion (Bufe and Lester, 1975).

No map of thermal gradients or heat flow has ever been presented for The Geysers-Clear Lake region although rumored heat-flow values exceed 4 HFU (Jamieson, 1976). The known temperature of The Geysers steam reservoir is approximately 240°C to a depth of about 4000 m. Northeast of The Geysers, beneath the Clear Lake Volcanics, temperatures of over 200°C have been encountered at depths as shallow as 2000 m (Goff et al., 1977).

V. HYDROLOGY AND THERMAL FLUIDS

Surface Hydrology: Integrated studies of near surface hydrology have never been performed for the entire Clear Lake region. Major investigations have been carried out in Big Valley, and adjacent basins north of the Clear Lake Volcanics (Lake Co. Flood Control and Water Conservation District, 1967). These valleys, which drain into the north arm of Clear Lake, yield large quantities of water from many shallow aquifers for extensive irrigation of orchards and vineyards. Overpumping and lowering of the water table has been a problem in Big Valley.

The Cache Formation, although it is largely unconsolidated and occupies a structural basin, does not possess a known potable aquifer of large extent (Upson and Kunkel, 1955). The Clear Lake Volcanics, because of their porous nature, soak up large quantities of water and yield many cold springs of varying size from the base of the volcanic sequence. No extensive aquifers are known to exist in either the Franciscan assemblage or the Great Valley sequence within the Clear Lake region, probably because of their chaotic and broken geologic structure. Local accumulations of sediment along stream valleys and in small basins possess many small aquifers of potable water. Cold springs throughout the region discharge from landslides, from contacts of lithologic units, and from faults or fractures.

Water quality of a large number of small potable aquifers and springs has been reported in the literature (Lake Co. Flood Control and Water Conservation District, 1967; Upson and Kunkel, 1955; Berkstressor, 1968; Thompson et al., 1978). Fluoride concentrations regionally tend to be less than 1 mg/l. In general, potable waters in the Clear Lake Volcanics tend to be silica-rich (50-70 mg/l) relative to other source lithologies. On the other hand, potable waters from other units, especially the Great Valley sequence, possess relatively higher salinities including boron (Thompson et al., 1978).

Thermal Fluids: The Geysers-Clear Lake region possesses a remarkably diverse suite of thermal waters that have been investigated in some form for nearly 100 years (e.g., Waring, 1915). A more detailed review of this subject is covered in the companion volume by White, and only a few high points will be discussed here.

Two major chemical types of thermal water discharge in the region (Goff et al., 1977): 1) Steam condensate and derivative waters associated with The Geysers steam field, and 2) relatively chloride, bicarbonate-rich waters from areas surrounding the steam field, but particularly north and east of the Collayomi fault zone. Steam condensate waters which are typically high in sulfate and low in pH, are characteristic of vapor-dominated geothermal reservoirs such as The Geysers (White et al., 1971). They are generally composed of condensed water vapor and oxidized H_2S that have risen from the underlying steam reservoir.

Thermal waters of the second type display wide ranges in chemical and isotopic composition (i.e., Barnes et al., 1973b) which are strongly correlated with flowage through either Franciscan or Great valley rocks as well as with temperature (Goff et al., 1977; Goff and Donnelly, 1978). Type 2 thermal water is highly controversial both in sub-classification and in interpretation of origin (White, 1957; White et al., 1973; Barnes et al., 1973a) due to the variety of geothermal environments, to complexity of the bedrock structure, and to compositional correlations with lithology and temperature. No thermal waters originate in the Clear Lake Volcanics. All thermal waters rise from depth along faults or fractures.

Geothermal Regimes. The distribution of type 1 and type 2 thermal waters was combined by Goff et al. (1977) with available geology and geophysics to delimit the extent of the vapor-dominated system at The Geysers (Fig. 9). The system is apparently bounded on the southwest by the Mercuryville fault zone,

Fig. 9.

Approximate inferred limits of vapor-dominated and hot water-dominated areas; heavy lines are major fault traces; Goff et al. (1977).

which is the western-most limit of extensive hydrothermal alteration (McLaughlin, 1977). The southeastern and northwestern limits are ill-defined geologically, but no steam has been found to date outside these limits. The northeastern limit is the Collayomi fault zone, which also corresponds with sharp gradients in the gravity and electrical resistivity data. All type 1 thermal waters are restricted to the vapor-dominated zone as shown in Fig. 9.

Water-dominated geothermal reservoirs are confined to areas that discharge type 2 thermal waters, particularly north and east of the Collayomi

fault zone. Distinct chemical signatures from waters in local areas indicate there are several small structurally controlled water-dominated geothermal reservoirs rather than one large one. Significant reservoirs are located in the Wilbur Springs District (Thompson, 1979) and at Sulphur Bank Mine (White and Roberson, 1962). Smaller reservoirs of unknown temperature apparently exist along the Bartlett Springs fault zone, along the Wilson Valley fault zone near Chalk Mountain, along the Konocti Bay fault zone near Clear Lake, in the Big Canyon area near Howard Springs, and in the Sulphur Mound Mine area south of Mt. Konocti.

Although the basement rocks beneath the volcanic field are as hot as 200°C at only 2000 m depth, exploration drilling for hot-water reservoirs has been largely unsuccessful due to impermeability. Apparently, hydrothermal reactions caused by the magmatic heat source seal up the majority of buried graywackes faster than the active tectonic environment can fracture them. The impermeable nature of the basement may make the region beneath the Clear Lake Volcanics more suitable for geothermal development by hot dry rock methods rather than conventional methods (LASL report, 1978; Tester et al., 1979). The prototype HDR system at Fenton Hill, New Mexico has been constructed in an impermeable reservoir of Precambrian granite. It currently is not known how difficult it would be to construct a similar reservoir in impermeable graywacke. Los Alamos Scientific Laboratory is about to investigate this possibility.

VI. UNRESOLVED PROBLEMS

Many unresolved problems of all types remain in The Geysers-Clear Lake region, some of which can be solved by extensive deep drilling. It is unlikely that one deep hole could possibly solve all of the problems. Perhaps the most nagging unknown is the answer to question 1 below, which one deep hole could solve.

Major Research Problems:

1. Does a deep boiling brine provide steam for The Geysers vapor-dominated reservoir?
2. Where is the potent heat source that supplies The Geysers? Is it below the vapor-dominated zone or is it coupled to a magmatic source beneath the Clear Lake Volcanics?

3. Why is The Geysers geothermal field south of the main Clear Lake Volcanics, although the youngest volcanic rocks lie well to the north?
4. What governs recharge of the two geothermal provinces? Why does a vapor-dominated zone exist south of the Collayomi fault zone while only hot-water zones are found to the north and east?
5. What is the basement geology and structure beneath The Clear Lake Volcanics?
6. What is the heat flow pattern in The Geysers-Clear Lake region?
7. What geophysical methods can effectively find hot-water reservoirs beneath The Clear Lake Volcanics?
8. Do most surface hot springs originate from deposits of hot-water of possible economic importance?
9. How fast will the vapor-dominated zone be depleted? Will exploitation of geothermal reservoirs ruin surface hot springs?

Topical Research Problems:

1. What is potential for volcanic hazards?
2. How does volcanism of the Coast Ranges fit the regional picture of subduction, transform faulting, and continental hot spots?
3. What are the environmental hazards due to landslides, and geothermal impacts on hydrology (e.g., Crow, 1979)?
4. How can we improve geothermal well stimulation techniques?

VII. CONCLUSIONS

The Continental Scientific Drilling Program specifically mentions The Geysers vapor-dominated system as a target for deep continental drilling of a magma-hydrothermal system (U.S. Geodynamics Committee, 1979). One fundamental problem that will be answered in The Geysers (as mentioned above) is to discover if a deep boiling brine supplies the steam to this vapor-dominated reservoir. Also, a deep hole could possibly resolve what the local heat source is beneath The Geysers and could possibly unravel deeper geologic structure in the Franciscan assemblage. Although several private companies have drilled over 100 deep holes into the vapor-dominated reservoir, it is not certain whether or not they will ever drill an extremely deep one (5-8 km).

A second location that could provide answers to many questions would be in the Clear Lake Volcanics near the center of the large negative gravity anomaly. A deep hole there could possibly encounter crystallized magma in shallow sills, dikes, and plugs from the underlying magma reservoir. Such a hole could also pass through the hot saline reservoir inferred from the 3 ohm-m electrical resistivity low, and could tell us much about low-to-medium grade metamorphism of Franciscan basement. Deep drilling in this area, where subsurface temperatures reach 200°C in only 2000 m, is certain to encounter severe drilling problems and would necessarily result in design of sophisticated drilling equipment. Finally, this hole could help unravel subsurface stratigraphy and structure associated with the Coast Range thrust beneath the volcanic field.

This author feels that no other sites except these two are worthy of deep continental drilling in this region. The three major surface hydrothermal systems, Calistoga, Sulphur Bank Mine and Wilbur Springs District, have already been drilled and are not associated with the main volcanic pile, significant geophysical anomalies, or with the relatively rare vapor-dominated reservoir.

GEOLOGY OF THE LONG VALLEY CALDERA, CALIFORNIA

by

D. Emerson and J. Eichelberger

ABSTRACT

Long Valley Caldera is a large Quaternary silicic volcanic complex that lies at the boundary of Sierra Nevada escarpment on the west and the Basin and Range tectonic province to the east. Silicic volcanic rocks and associated sediments overlie a faulted basement of Mesozoic granite and Paleozoic metasediments. Surface hydrothermal phenomena include sulfur fumaroles at Casa Diablo and a variety of hot springs as hot as 63°C. Extensive subsurface investigations with both shallow and deep wells show that modest-size hydrothermal systems, as hot as 169°C, are perched in permeable aquifers above colder rocks at shallow stratigraphic levels in the Caldera. Thermal gradients in deep wells are not known to be above 37°C/km. In contrast, limited geophysical data suggest that a magma reservoir extends from 7 km to as much as 25 km beneath the surface. A deep drill hole (5-8 km) might resolve these contradictions and provide data for either confirming or rejecting the geophysical interpretations.

I. INTRODUCTION

Long Valley Caldera is an elliptical depression, 17 km wide by 32 km long, on the east side of the Sierra Nevada 50 km northwest of Bishop, California. As described by Bailey et al. (1976), it formed 0.7 Myr ago during the eruption of the Bishop Tuff. Post-collapse intracaldera activity included rhyolitic eruptions and resurgent doming 0.68-0.64 Myr ago, rhyolite from peripheral vents 0.5-0.1 Myr ago, and rhyodacite from outer ring fractures 0.2-0.05 Myr ago. This sequence may record progressive crystallization of a zoned magma chamber. Holocene rhyolitic and phreatic eruptions occurred as recently as 450 years ago. Hydrothermal activity was previously widespread within the caldera. Starting at least 0.3 Myr ago, it has declined due to self-sealing mineralization and has now become localized in permeable aquifers adjacent to recently reactivated northwest-trending Sierra Nevada frontal faults.

Teleseismic (Steeple and Iyer, 1976) and seismic refraction data (Hill, 1976) suggest that a magma reservoir extends from 7 km downward to as much as 40 km beneath the resurgent dome. A deep drill hole on the resurgent dome would penetrate the hottest part of the hydrothermal system and possibly provide an opportunity to study active or recently crystallized magma at a depth of 3 to 6 km (Smith and Bailey, 1968).

II. REGIONAL GEOLOGY AND TECTONICS

Much of the geology of east-central California has been mapped by the US Geological Survey, and the work is still in progress. These studies have resulted in geologic maps and reports on the Mono-Long Valley region by Rinehart and Ross (1957; 1964), Bateman (1965), Huber and Rinehart (1965), Kistler (1966a; 1966b), and Krauskopf and Bateman (1977). The overviews of Bailey et al. (1976) and Lipshie (1979) have been extensively used for this summary.

The pre-Tertiary basement rocks in the immediate vicinity of Long Valley Caldera are Jurassic and Cretaceous granodiorites and granites of the Sierra Nevada batholith and Paleozoic and Mesozoic metamorphic rocks of the Mount Morrison and Ritter range roof pendants (Bateman et al., 1963; Rinehart and Ross, 1964)(Fig. 10). Overlying the basement rocks on an erosion surface of moderate relief are late Tertiary volcanic rocks, mainly basalt, andesite, and rhyodacite. The wide and sporadic distribution of precalders volcanic centers suggests that these Tertiary rocks are not directly related to the Long Valley magma chamber, although they may represent an early part of the volcanic cycle that culminated with the voluminous rhyolites of Long Valley. These Tertiary volcanic rocks range in age from 3.2 to 2.6 Myr old (Bailey et al., 1976).

III. CALDERA FORMATION AND STRUCTURE

About 2 Myr ago, an arcuate fracture zone developed along the northeastern margin of the not-yet-formed Long Valley caldera. The rhyolite flows of Glass Mountain (Fig. 11), which are the oldest rocks associated with the Long Valley magma chamber, were extruded along the incipient ring-fracture system. The Glass Mountain rhyolites are believed to have been emplaced over a period of 1 Myr, from 1.9 to 0.9 Myr ago.

The next major event in the formation of the Long Valley caldera was the catastrophic eruption of the Bishop Tuff about 0.7 Myr ago. About 500 km³

Fig. 10.

Generalized geologic map of Long Valley caldera from Bailey et al. (1976).

of ash flows and 300 km^3 of airfall ash were emplaced within a time span of no more than a few centuries (Dalrymple et al., 1965). Eruption of the Bishop Tuff partially emptied the magma chamber, and the roof of the chamber collapsed, forming the elliptical depression of the caldera. Caldera subsidence totals 3 km, of which one-third is reflected in present topographic relief and the other two-thirds are represented by the Bishop Tuff and post-collapse tuffaceous basin fill (Fig. 11). The eastern part of the caldera has extensive

Fig. 11.

Schematic east-west cross section through Long Valley caldera and its subjacent magma chamber. Heavily dotted part of chamber is rhyodacitic magma; lightly dotted part is rhyolitic magma. Horizontal dotted lines show silica gradient in vertically zoned chamber. Curved dashed lines show depth to residual magma at specified times. The vertical scale is unspecified because of uncertainties in subsurface data. Pre-Cenozoic metamorphic rocks are included with granitics in cross section; figure from Bailey et al. (1976).

lake deposits that accumulated in Long Valley Lake (Mayo, 1934), a Pleistocene lake that filled the basin formed by the collapse of the caldera.

Shortly after collapse, the central part of the caldera underwent resurgent doming during which rhyolite was erupted from at least twelve vents. Doming and rhyolite extrusion in the central region were probably completed by 0.5 Myr ago, producing a "resurgent cauldron" with an uplifted central dome surrounded by a "moat" (Fig. 10). The next phase of Long Valley volcanism was the emplacement of marginal (moat) rhyolites in three discrete episodes: 0.5, 0.3, and 0.1 Myr ago. The moat rhyolites, emplaced on the periphery of the central dome, are probably related to ring fractures around the resurgent dome. A later stage of volcanism produced rhyodacite in the western part of the caldera between about 180 000 and 50 000 years ago. The main mass of these rhyodacite flows comprises Mammoth Mountain. During late Pleistocene time, basalt and andesite flows were extruded in the west moat of the Long Valley caldera. Ages of these flows range from 222 000 to 62 000 years. Near the towns of Mammoth Lakes within the caldera and June Lake to the north, basalt flows are interbedded with glacial deposits.

The most recent volcanic activity in the Mono-Long Valley region occurred in the Inyo Craters group, along the northwest margin of the Long Valley caldera. Three of the rhyolitic to rhyodacitic Inyo domes are probably less than 800 years old. The Inyo domes and craters are inferred to lie along a north-trending fracture that extends from the Long Valley caldera to the Mono Craters along the Sierra Nevada range front. An Inyo Craters eruption about 720 years ago produced a widespread tephra layer that blanketed much of the southern Sierra Nevada. The most recent volcanic event in the Mono-Long Valley region was the phreatic explosion that formed the southernmost Inyo crater around A.D. 1400 (Rinehart and Huber, 1965).

Hill (1976) and Kane et al. (1976) used seismic and gravity data respectively to estimate the total thickness of Long Valley caldera fill. They calculated a total thickness for Quaternary sedimentary and volcanic fill of about 2 km in the southwestern part of the caldera and about 3 km in the northeastern part. A wildcat geothermal well (Long Valley no. 66-29) was drilled jointly by the City of Burbank and Republic Geothermal, Inc. in 1976 to a depth of 2110 m. The well encountered sedimentary fill in the upper 335 m, early post-caldera rhyolite tuff in the depth interval from 335 to 697 m, and Bishop Tuff in the remaining 1413 m of the hole (Smith and Rex, 1977). Drilling was halted before the well penetrated the granitic-metamorphic basement rocks presumed to lie at depth; however, based on stratigraphy, these rocks are probably only 300 m deeper (R. Bailey, personal communication).

Using seismic refraction profile data, Hill (1976) identified a low-velocity region beneath the caldera at a depth of 7 to 8 km. He suggested that this velocity contrast represents the top of a residual magma chamber. Steeples and Iyer (1976) used teleseismic data to recognize a low-velocity zone beneath the caldera that they attributed to anomalously high temperatures, due to either magma or hot rock. They inferred that any magma chamber that exists is at a depth of at least 7 km and probably does not extend below a depth of about 25 km. These data indicate that the low-velocity region is confined to the western part of the caldera.

IV. HYDROTHERMAL SYSTEM

In general, hydrothermal activity (Bailey et al., 1976) follows the caldera moat and is therefore thought to be controlled by the caldera ring fractures. A keystone graben, aligned as an extension of a major fault of the

Sierra front, cuts the dome and displaces its surface by about 200 m. This region is the current focus of geothermal exploration. Active fumaroles occur only along young faults within the graben. Hydrothermal deposits and extensive alteration of caldera fill indicate that surface manifestations of hydrothermal activity were greater in the past (Bailey et al., 1976) and may have peaked at 0.3 Myr ago (Smith, 1976). Some variations in surface activity may be due to self sealing and to rupturing of the seal by Sierran tectonic activity. Major factors influencing the hydrothermal system and controlling distribution of hot springs and fumaroles are the caldera structure, the location of the magmatic heat source (as indicated by the resurgent dome and recent volcanism), self sealing by hydrothermal alteration, massive subsurface influx of cold Sierra water via faults to the west, and recent faulting. Hot spring chemistry indicates that the temperature of the hydrothermal reservoir is above 200°C (Muffler and Williams, 1976). Temperatures as high as 177°C at 120 m were encountered in shallow wells (Mariner and Willey, 1976).

A reservoir water sample obtained from Bishop Tuff during a drill stem test of a porous zone in the depth interval 1541 to 1614 m in Republic well no. 66-29 was similar to the dilute $\text{Na-HCO}_3\text{-Cl}$ waters of Long Valley hot springs, but modified by contamination with drilling cement. Its silica geothermometer temperature was 196°C.

Two recent wells drilled by Union Oil Co. (data courtesy of W. Isherwood, USGS, Menlo Park) in the vicinity of the resurgent dome achieved bottom-hole temperatures $\leq 160^\circ\text{C}$ although depths approached 2000 m. Temperature versus depth profiles from each well display irregularities due to aquifers in the upper rock units, particularly Bishop Tuff. In addition, these profiles clearly indicate that the hot aquifers are stratigraphically perched at high levels, because temperatures drop off once these aquifers are penetrated. A thermal gradient calculated from the bottom interval of one well is merely 37°C/km even though this hole bottomed in relatively impermeable granophyre (the other well has a lower gradient). This gradient is not high enough to indicate magma at shallow depths; thus, it may be that the magma reservoir remaining from formation of Long Valley caldera has crystallized.

V. PROBLEMS AND CONCLUSIONS

Long Valley has been thoroughly studied by surface and shallow-hole techniques and is at an early stage of deep exploratory drilling. Much of the

USGS data has been published, but petrologic work on surface samples (R. A. Bailey and R. Koeppen, USGS, Reston, VA) and cuttings from a deep well (Reba Fournier, USGS, Menlo Park, CA) is continuing.

At the present time, only the Republic Long Valley no. 66-29 well can be considered for scientific use. Unfortunately, its location would not have been a first priority choice for research, since it is removed from the focus of recent volcanic and hydrothermal activity. However, it offers a high probability of successfully reaching basement within the caldera. This would provide an important test of geological and geophysical models (structure and eruption history), an opportunity to investigate fracturing of the caldera block associated with collapse, and an opportunity to measure conduction-dominated heat flow and thereby constrain thermal and hydrologic models. Because the hole is not cased for most of its length, the caldera-fill hydrothermal system can be sampled from top to bottom, utilizing fluid sampling and side-wall sampling techniques. These data on conductive and convective heat transfer would determine whether relatively low temperatures in this part of the caldera are due to influx of cold water or absence of underlying magma.

In view of the relatively low temperatures encountered in the caldera fill in the southeast moat and the improbability of a commercially useful hydrothermal system in granitic basement, it seems unlikely that industry will drill any more deep holes in the eastern 40% of the caldera (White, 1976).

If deep commercial or scientific exploration of the dome continues, then the Republic well in the southeastern moat will provide an important complement to data from the dome in constraining models of the hydrothermal and magmatic systems. For scientific information, the best location of a deep hole would probably be on the resurgent dome. As shown in Fig. 11, this is the closest approach to the shallow high temperature hydrothermal system and to the center of the magma system.

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GEOLOGY OF THE RIO GRANDE RIFT

by

J. C. Eichelberger and H. R. Westrich

ABSTRACT

The Rio Grande rift is a series of en echelon grabens, which extend from central Colorado across New Mexico and into northern Chihuahua. This rift system is geographically divided into three parts: the northern, middle, and southern segments. Each segment is characterized by high heat flow, recent volcanism and faulting, and an anomalously thin crust, although some portions of the southern segment are not easily distinguished from adjacent physiographic provinces. Only the middle and southern segments of the Rio Grande rift exhibit sufficient geologic evidence to warrant comprehensive deep drilling by CSDP. These sites include the Socorro region of the southern segment where a midcrustal magma body is postulated from limited geophysical data. The second site is the Valles Caldera where the Jemez Lineament intersects the middle segment of the Rio Grande rift. Deep drilling at both sites would enable proper evaluation of the structural and tectonic features of a major continental rift system and would permit geophysical and geologic modeling of active geothermal regimes.

I. INTRODUCTION

The Rio Grande rift (Fig. 12) is an elongate series of en echelon grabens that extend from northern Mexico across New Mexico to central Colorado (Chapin, 1979). Throughout most of its length, this structural system possesses all the characteristics thought to define a rift system including recent volcanism and faulting, high heat flow, high mantle electrical conductivity and a relatively thin crust. This rift system is one of the largest in North America and began to form about 29 Myr ago. Because the rift is approximately 1000 km long and traverses many pre-existing structures, it is appropriate to divide it into three segments in discussing its geologic setting.

The northern segment, essentially that portion of the rift within Colorado, encompasses the San Luis and Arkansas Valleys and lies wholly within the area of Southern Rocky Mountain structures of Laramide age. The middle segment lies between the Colorado Plateau on the west and the Southern Rocky

Fig. 12.
Principal features of the Rio Grande rift.

Mountains and High Plains on the east. It encompasses, from north to south, the Taos Plateau, Espanola basin, and Albuquerque basin. From Socorro south to northern Mexico and west Texas, the southern segment of the rift broadens to include several subparallel grabens, including the Palomas-Mimbres-Los Muertos, Mesilla-Jornado del Muerto, and the Tularosa-Hueco basins. This segment of the rift forms a sharp border with the High Plains to the east, but is not easily distinguished from the Basin and Range Province to the west. Emphasis will be placed on the middle segment of the Rio Grande rift because it exhibits abundant geologic evidence of active magmatic and hydrothermal systems.

II. NORTHERN SEGMENT

A. Regional Geology

The Southern Rocky Mountains have been the site of repeated uplift since late Precambrian time (Tweto, 1975, 1979a), so that the sedimentary record for the northern rift region is limited. The basement of this region consists of highly deformed 1.8 b.y.

gneisses, intruded by granitic bodies of both later Precambrian (1.7 b.y.) and Laramide ages (Tweto, 1979b). The northern terminus of the rift intersects the Colorado Mineral Belt, which appears to have been a zone of major lateral movement in Precambrian time (Tweto and Sims, 1963). Uplift of the region in early Paleozoic time and again during the Laramide Orogeny (late Cretaceous to early Tertiary) stripped off the lower Paleozoic and Mesozoic sedimentary

cover, and shed arkosic Precambrian debris into surrounding basins. The next major event was the development in mid-Tertiary time of widespread igneous activity within the region of Laramide deformation (Steven, 1975). The San Juan Volcanic Field, which borders the western side of the San Luis Valley, is the largest remnant of products of this activity. Volcanism was intense from 35 to 26 Myr ago (Oligocene) and spread a 1 km thick cover of volcanic material over the present San Luis Valley and Sangre de Cristo regions. Deposition of sediments due to rifting began during the close of this activity.

Late Tertiary rift sediments and mid-Tertiary volcanic rocks and alluvium lie directly on Precambrian basement beneath much of the San Luis Valley. Farther north and away from the axis of the late Paleozoic Uncompahgre-San Luis Highland, Paleozoic sedimentary rocks are preserved beneath the basin fill (Davis and Stoughton, 1979). The thickest section of Miocene to Quaternary rift sediments known from drilling in the San Luis Valley is 2.6 km (Tweto, 1979a). Alluvial fill in the Arkansas Valley is about 1 km thick.

B. Tectonics

The major grabens considered here as part of the Rio Grande rift are part of a large region of normal faulting in the Southern Rocky Mountains, associated with the uplift of this region in late Tertiary and Quaternary time. Most of these faults are Precambrian structures which have been repeatedly reactivated (Tweto, 1979a). Thus, while the cause of development of the rift structure is extension, the form of the rift is largely controlled by earlier events.

The San Luis Valley, like other portions of the rift, is asymmetrical (Fig. 13). While the eastern boundary is a narrow fault zone of high structural relief, the western boundary, where exposed, is a dip slope of eastward tilted Oligocene volcanic rocks to the surface near the New Mexico border and can be traced well to the north beneath Quaternary fill with gravity and well data (Tweto, 1979a). Downward displacement of the San Luis Valley relative to the Sangre de Cristo Range is about 6 km based on well data. This is considerably less than previously predicted from gravity data.

Development of the northern segment of the Rio Grande rift may have begun as early as 26 Myr ago as suggested by appearance of alkali olivine basalt, common to the rift, in the eastern San Juan Volcanic Field (Lipman and Mehnert, 1975). Major uplift of the Sangre de Cristo Horst along the east

Fig. 13.

Cross sections of the northern, middle, and southern segments of the Rio Grande rift. Lines of cross sections are shown in Fig. 11. Depth of basins is partially constrained by well data in north and south segments and by gravity data in middle segment. Data sources are: (North segment) Tweto (1979a,b); (Middle segment) Smith et al. (1970), Kelley (1978), Smith and Bailey (1968), Budding (1978), F. E. Goff, LASL written commun. (1980); (South segment) Seager and Morgan (1979), Hoffer (1976), Glover (1975), Beane et al. (1975). Elevation is in meters.

margin of the San Luis Valley occurred 7 to 5 Myr ago (Tweto, 1979a). Faults have displaced 4700 yr old alluvium and 100 yr old mine timbers on the east sides of the San Luis and Arkansas Valleys, respectively (Kirkham and Rogers, 1978).

C. Igneous Activity

Volcanism in the region of the northern rift reached a maximum before the onset of rifting with development of the San Juan Volcanic Field (Steven, 1975). San Juan activity began about 40 Myr ago with eruption of andesitic lavas and culminated with voluminous silicic ash flow eruptions. Contemporaneous basaltic and rhyolitic (bimodal) volcanism, which Lipman and Mehnert (1975)

correlate with early rifting, occurred from 27 Myr to 20 Myr. This was succeeded by basaltic volcanism, for which the youngest date is about 4 Myr. Thus the record of igneous activity during rifting is one of decline in volume and petrologic diversity; there is no Quaternary volcanism.

D. Hydrothermal Systems

Hot springs are associated with faults in both the San Luis and Arkansas Valleys (Tweto, 1979a). Wells have encountered gradients as high as 60°C/km near Alamosa (Edwards and others, 1978), reflecting the presence of graben fill with low thermal conductivity in a normal southern Rocky Mountain heat flow regime. There is no evidence of high-temperature hydrothermal systems.

E. Problems

Considerable surface geologic and drilling data is available for the northern segment, but from the standpoint of understanding active hydrothermal and magmatic systems, this is probably the least interesting segment of the rift.

III. MIDDLE SEGMENT

A. Geology

The middle segment of the rift is the best defined portion in terms of structure. It also possesses all the features thought to define the rift: relatively young volcanism, high heat flow, relatively thin crust, and high mantle conductivity. Except for crustal thickness, however, none of these features coincide with the position of the rift as indicated by structural features. A major complicating factor is intersection of the Jemez Zone, a northeast-trending alignment of late Tertiary and Quaternary volcanic centers, with the middle segment of the Rio Grande rift at the Jemez Volcanic Field. While vertical tectonism can be clearly assigned to rifting, the Jemez Zone is a more important feature in terms of volcanism and may be as important in terms of heat flow.

Most of the major uplifts in this portion of the rift expose Precambrian basement. Exposures are nearly continuous along the east side of the rift in the Sangre de Cristo, Sandia, and Manzano Mountains. More isolated glimpses of the basement are provided by the Tusas Mountains west of the Taos Plateau, the Sierra Nacimiento west of the Espanola basin, Ladron Peak at the southwest end of the Albuquerque basin, and a small horst which blocks the south end of

the Albuquerque basin between the Ladron and Manzano uplifts (Dane and Bachman, 1965). Precambrian metamorphic rocks include quartzite, schist, gneiss, amphibolite, and metarhyolite. In the Nacimiento, Sangre de Cristo and Sandia uplifts, metamorphic rocks, some deformed during the period 1.8 to 1.7 b.y., are intruded by relatively undeformed granitic plutons of 1.7 to 1.1 b.y. age (Brookins et al., 1977; Condie, 1979; Register and Brookins, 1979; Brookins, 1973; Kelley and Northrop, 1975).

The pre-Cenozoic sedimentary section thickens southward. North of the Sierra Nacimiento and Jemez Mountains, Mesozoic strata rest directly on the Precambrian because the late Paleozoic Uncompahgre-San Luis Highland extended into this region. Farther south, the unconformable contact between late Paleozoic marine sediments and Precambrian basement is prominently displayed near the crest of the Sandia and Manzano Mountains. Pennsylvanian rocks are dominantly limestone while both the Permian and Mesozoic sections contain numerous red sandstones and evaporites. Lower Tertiary strata of sandstone, shales, and conglomerates lie unconformably upon Mesozoic rocks but predate rifting. Volcanic material late in this sequence and related intrusives of the Ortiz Mountains, southwest of Santa Fe, correlate with mid-Tertiary volcanism in Colorado (Manley, 1979). Rifting produced a thick sequence of Miocene to Pleistocene sands and gravels, shed into the basins by surrounding uplifts. The significant volcanic component in these deposits came from erosion of the mid-Tertiary volcanic fields, from a major silicic igneous center located east of the Taos Plateau and dated at 23 Myr (Pillmore et al., 1973), and finally from the Jemez field located on the west side of the Espanola Basin and dated at 10 Myr to nearly the present (Manley, 1979). A well at the north end of the Albuquerque basin, near the center of this rift segment, penetrated 850 m of Tertiary rift sediments, 240 m of Tertiary pre-rift sediments, 1580 m of Mesozoic strata, 640 m of upper Paleozoic rocks, and reached basement at 3.3 km (Hiss et al., 1975).

B. Tectonics

The three grabens of this segment of the rift are arranged in an echelon fashion, with the Espanola basin offset about 50 km east of the Albuquerque-Belen basin and the Taos basin offset about 30 km east of the Espanola basin. Dips of the basins reverse across these offsets, so that the Espanola basin deepens to the west, while both the Albuquerque-Belen and Taos basins deepen

to the east (Kelley, 1979). The thickest section of rift sediments known from drilling is 4 km in the Albuquerque basin, implying a total vertical displacement relative to the Sandia uplift exceeding 7 km. No deep holes exist in the Espanola basin (Fig. 13), but about 3 km of basin fill on the deeper west side of the basin is suggested by gravity data (Budding, 1978). Fill beneath the Taos Plateau may be 5 km (Lipman and Mehnert, 1979).

Evidence that tectonic activity continues to present exists in all three basins. Small scarps cut Holocene deposits in both the Albuquerque basin (Kelley, 1977) and Taos Plateau (Lipman and Mehnert, 1979). The most prominent western boundary fault of the Espanola basin displaces Bandelier Tuff of 1.1 Myr age by as much as 200 m and is still seismically active (Sanford et al., 1979). Much larger displacement of the basement by this fault is indicated by gravity data (Cordell, 1978).

The Jemez Zone (Mayo, 1958; Laughlin et al., 1976), a zone of voluminous late Tertiary and Quaternary volcanic activity and possible tectonism as early as Precambrian time, intersects this segment of the rift. The only extensive young (<5 Myr) volcanic fields within the rift, and the only young silicic volcanism within the rift, are near this intersection.

C. Igneous Activity

The middle segment of the rift has experienced two important episodes of igneous activity. The first was most extensive in Oligocene time, but continued during early rifting with emplacement of rhyolitic tuffs and granitic intrusives centered east of the Taos Plateau (Lipman and Mehnert, 1979). The second culminated within the last few million years with development of the Jemez and Taos volcanic fields. The Taos field (Lipman and Mehnert, 1979) is the smaller of the two and the more restricted in time, with dates ranging from 4.5 to 2.0 Myr. During this period, the entire region of the Taos Plateau was flooded with tholeiitic basalt. Alkali olivine basalt, andesite, dacite, and rhyolite are also present. In general, the lavas are aphyric and those more silicic than basalt comprise shields or domes, each petrologically homogeneous.

The Jemez Volcanic Field (Smith et al., 1970; Bailey et al., 1969; Smith and Bailey, 1968; Smith and Bailey, 1966; Leudke and Smith, 1978), located at the intersection of the Jemez Zone and the Rio Grande rift on the western margin of the Espanola basin, began its activity about 10 Myr ago and has continued its development virtually to the present. From 10 to 8 Myr ago, activity

was centered on the south side of the field and involved growth of large strato-cones built of porphyritic andesite flows (Paliza Canyon Formation). This was followed by extrusion of voluminous porphyritic dacite domes and stubby flows on the north side of the field, for which dates of 7 to 4 Myr have been determined (Tschicoma Formation). These dacite domes are aligned in north-south trending arrays and are cut by north-south trending faults. Beginning about 3 Myr ago and continuing until between 1.4 and 1.1 Myr, tholeiitic and alkalic basalts erupted from the north, south, and southeast flanks of the field (Smith et al., 1970; Baldrige, 1979). Many of these vents also show a north-south alignment and could be related to rift faulting, although the connection between tectonics and volcanism is currently obscure. Two voluminous ($>100 \text{ km}^3$ each) eruptions of rhyolitic magma from the center of the field followed, one at 1.4 Myr and one at 1.1 Myr (Doell et al., 1968). These events formed the lower and upper members of the Bandelier Tuff, respectively. Both eruptions involved caldera collapse in the source region, with subsequent resurgence. Formation of the Valles Caldera during the second event largely obliterated the older Toledo Caldera. Collapse of the Valles Caldera involved as much as 2 km of vertical displacement and resurgence of at least 1 km (Smith and Bailey, 1968; Dondanville, 1978). Moderate volume (1 to 10 km^3) eruptions of rhyolitic lava and tephra have continued from the time of caldera formation almost to the present (Doell et al., 1968). Relative to the precaldern activity, extrusives of the caldera stage tend to be more silicic, less crystal-rich, and contain a much larger proportion of pyroclastic material.

The rapid emplacement of a large volume, compositionally zoned ash flow sheet accompanied by volumetrically comparable collapse in the source region suggests withdrawal of magma from a single large, shallow, compositionally zoned pluton (Smith and Bailey, 1968). Large geothermal anomalies with heat flow values ranging from 3.0 to 5.0 HFU (Reiter et al., 1975; Sanford et al., 1979) as well as deep thermal waters with temperatures exceeding 260°C (Dondanville, 1978) have been measured within the caldera and suggest the presence of a shallow magmatic heat source.

Apparently, little Tertiary pre-rift or early rift volcanism has occurred in the region of the Albuquerque basin, although numerous, but volumetrically minor tholeiite and alkali olivine basalt volcanoes have erupted along north-

south fissures during the last million years (Baldrige, 1979). Activity at the largest of these fields, Albuquerque Volcanoes and Cat Hills, occurred between 0.2 and 0.1 Myr ago (Luedke and Smith, 1978).

D. Hydrothermal Activity

Numerous thermal springs are present within the middle segment of the rift. They occur on both sides of the Taos Plateau, but generally on the west side of the Espanola and Albuquerque basins, coincident with the pattern of high heat flow (Grim, 1977; Reiter et al., 1975; Edwards et al., 1978).

The only known high-temperature hydrothermal system in the rift lies within the Valles Caldera (Dondanville, 1978). The caldera is an ideal environment for development of hydrothermal activity, because it represents a closed structural basin filled with permeable volcanic debris and located directly above a large, shallow, long-lived magmatic heat source. Fracturing of the central structural dome during resurgence has enhanced permeability in the portion of the system closest to the heat source.

Surface manifestations of hydrothermal activity include localized fumaroles and more widely distributed hot springs and gas seeps (Dondanville, 1978). Some thermal waters within the caldera have low pH and high sulfate content. Hydrothermal alteration extends over an area of 40 km², generally coinciding with the resurgent dome.

Deep drilling has encountered a large, liquid-dominated, underpressured hydrothermal system at depths below 500 m within the resurgent dome (Dondanville, 1978). Fluids average 6000 parts per million (ppm) total dissolved solids and are produced principally from the nonwelded lower portion of the Bandelier Tuff. Fractures in underlying late Tertiary lavas, the Paleozoic section, and even the Precambrian granite basement also contribute to production. Most wells are 2 to 3 km in depth and at least one has reached Precambrian basement within the caldera. Temperatures as high as 300°C have been measured. Hot springs along major rift bounding faults southwest of the caldera appear to be mixtures of near surface meteoric waters and deep thermal waters from within the caldera (Trainer, 1975; Trainer and Lyford, 1979).

D. Problems

Resurgent cauldrons, of which the Valles Caldera is a type example, have been recognized throughout the world and are among the largest of volcanic features. Smith and Bailey (1968) identify seven stages through which most of

these volcanoes evolve and have proposed what is now a widely accepted model for caldera evolution. This model views caldera development as a record of emplacement of batholith-size magma bodies at depths of a few kilometers. Ash flows erupted during caldera collapse are believed to have emanated from caldera-bounding ring fractures rather than from central vents. The subsurface configuration of intrusions is represented by ring dike complexes such as those exposed in the Hebrides and described in great detail by the Geological Survey of Scotland memoirs covering Mull (1924), Arran (1928), and Ardnamurchan (1930). These multiple granitic ring dikes, of sizes comparable to ring fractures, surround a large central pluton that presumably underlies a resurgent dome. Volcanic rocks that accumulated on the subsided caldera block are preserved between the ring dikes and central pluton of some of the complexes. Deep drilling in the Valles Caldera could test important aspects of this model and the results would be applicable to other localities having silicic calderas. Additional geologic problems related to caldera formation could also be addressed through deep drilling in the Valles Caldera. They include careful examination of active geothermal systems and their associated hydrothermal alterations, and a comprehensive evaluation of the relationship between the Jemez Lineament and the tectonic and structural features of the Rio Grande rift.

IV. SOUTHERN RIFT

A. Geology

The southern segment of the Rio Grande rift consists of series of parallel, generally north-trending basins and ranges (Fig. 13) whose combined width is at least twice that of the middle and northern segments. This broadening occurs immediately south of what has been termed the Socorro constriction (Kelley, 1977). The eastern boundary of the southern rift with the High Plains is abrupt in its topographic, geologic, and geophysical (gravity, seismic properties, heat flow, mantle electrical conductivity) expression. The western boundary with the Basin and Range Province is less well defined. Structural, volcanic, and geophysical characteristics of the rift continue westward. The main argument for this segment of the rift being a feature distinct from the Basin and Range is that the rift basins are deeper and more active tectonically (Seager and Morgan, 1979). The southern termination of the Rio Grande rift is

also poorly defined. It is generally considered to extend southeast from the New Mexico border into west Texas and northern Chihuahua where the rift appears to end near the southern part of the Hueco and Los Muertos basins (Cordell, 1978; Chapin, 1979; Smith and Jones, 1979).

As with the other segments of the rift, some faults active during rifting originally developed as Laramide or even Precambrian basement structures. Basement beneath the southern rift is generally younger than basement to the north. Granitic igneous rocks yield 1.6 to 1.3 b.y. ages at the latitude of Socorro and a 1.0 b.y. age near El Paso (Budding and Condie, 1975; Muehlberger and Denison, 1969). The only extensive exposure of basement is on the east face of the San Andres Mountains and in the Franklin Mountains. The pre-Cenozoic sedimentary section is much thicker in the southern rift, due in part to the presence of a lower Paleozoic section absent to the north (Kottlowski, 1975). Pre-Permian strata thicken from the latitude of Socorro southward, while Permian strata thin and give way to more limestone (Hueco) and fewer red beds and evaporite deposits (Abo, Yeso). The main exposures of Mesozoic rocks are at the north end of the Jornada del Muerto and Tularosa basins, although as much as 760 m of Mesozoic rocks have been reported in wells in the southernmost rift (Thompson and Bieberman, 1975). Tertiary deposits include early Tertiary coarse clastic debris, a consequence of Laramide mountain building, and mid-Tertiary volcanoclastic deposits resulting from an Oligocene igneous event.

Major Oligocene igneous centers were the Mogollon Plateau west of the rift and the Sierra Blanca and Capitan area east of the rift (Elston and Barnhorst, 1979; Thompson, 1975). The Mogollon Plateau resembles the San Juan Volcanic Field in age, position at the edge of the Colorado Plateau, and style of activity, including development of voluminous tuffs and associated calderas. Rifting began between 32 Myr and 26 Myr ago, as evidenced by a change to bimodal volcanism in the Mogollon Plateau region and normal faulting of lavas (Chapin, 1979; Elston and Barnhorst, 1979; Seager and Morgan, 1979; Chapin and Seager, 1975; Seager, 1975). Early (Miocene) rift sediments accumulated in broad basins and later sediments (late Miocene to Pleistocene) filled numerous deep, narrow basins. A deep well in the Mesilla Basin, near the center of the southernmost rift, penetrated 0.6 km of rift-related sediments, 1.1 km of Tertiary volcanic rocks, 2.0 km of lower Tertiary sediments, and 2.9 km of what is estimated to be a 3.1 km Mesozoic and Paleozoic section (Foster, 1978). In

addition, numerous "andesitic" plutons are located in the Tertiary sediments in the Mesilla Basin (Lovejoy, 1976).

B. Tectonics

Development of the subparallel basins of the southern rift was controlled by Miocene and Pliocene extensional block faulting, which has continued until recent time (Seager, 1975). There are abundant late Pliocene and Pleistocene fault scarps in both the Socorro and Las Cruces areas (Chapin and Seager, 1975), and several faults as young as 4000 years old have been identified from Landsat photographs (Seager and Morgan, 1979). These faults are oblique to the general northwest trend of Miocene faulting in the southern Basin and Range. Tectonic activity appears to have been most intense during the period 10 Myr to 1 Myr ago and to have declined in Quaternary time (Chapin and Seager, 1975). This is consistent with the relatively low level of seismic activity observed at present (Sanford et al., 1979).

Alluvial fill in rift basins near Las Cruces reaches 2.5 km in thickness, in contrast to Basin and Range grabens of the surrounding region which appear to contain less than 1 km of fill (Seager and Morgan, 1979; although deeper basins are known in Arizona). Vertical structural displacement in the southern rift exceeds 8 km.

C. Igneous Activity

Like the northern rift, the southern rift experienced a major mid-Tertiary igneous event. However, the southern rift has been the site of late Tertiary and Quaternary activity as well. On the Mogollon Plateau, mid-Tertiary activity began with andesitic volcanism about 40 Myr ago and culminated a few million years later with eruption of voluminous rhyolitic ash flows and development of large calderas (Elston and Bornhorst, 1979). A change to bimodal volcanism was well established by 30 Myr and this style of activity continued until about 20 Myr. On the other side of the rift at the Sierra Blanca center, andesitic volcanism began at least 35 Myr ago and became progressively more felsic (Thompson, 1972). In this case, the felsic members were trachytic lavas and shallow syenitic intrusions. Activity continued at least until 16 Myr ago. Volcanism resumed about 14 Myr ago with eruption of basalts, although some rhyolite was extruded near Socorro. Late Tertiary and Quaternary activity in the southern rift consists almost entirely of alkali olivine basalt. Important sites of Quaternary volcanism are the West Potrillo

Mountains on the west side of the Mesilla Basin, the Jornada del Muerto field in the basin of the same name, and the Carrizozo Malpais at the north end of the Tularosa Basin (Hoffer, 1976; Smith, 1964; Luedke and Smith, 1978). The Potrillo and Carrizozo centers contain flows of Holocene age. Contemporaneous volcanism of similar composition has occurred at several nearby sites west of the rift, both in the Basin and Range province and within the Jemez Zone on the Colorado Plateau (Luedke and Smith, 1978). Although there has been no recent volcanism in the Socorro area, an active magma body has been proposed to exist in the crust in the vicinity of the Socorro constriction, based on seismic data (Sanford et al., 1977; Rinehart et al., 1979; Brown et al., 1979). The data suggest a thin, sill-like body exceeding 1700 km^2 in area and located at a depth of 19 to 20 km.

D. Hydrothermal Activity

Numerous thermal springs exist within the southern rift (Grim, 1977). A low-temperature ($<46^\circ\text{C}$) hydrothermal reservoir has been found at depths less than 1 km near Las Cruces (Gunaji et al., 1978). No high-temperature hydrothermal systems are known.

E. Problems

The southern rift has experienced recent tectonic and magmatic activity, but at a lower level than the middle segment. The presence of a midcrustal magma body near Socorro and its relationship to extensional rift faulting might warrant a program of deep drilling; however, its postulated depth (20 km) might make it prohibitively expensive or impractical.

V. SUMMARY AND CONCLUSIONS: RIO GRANDE RIFT

Two important sets of problems can be addressed by deep research drilling within this region: those related to the structure and evolution of calderas and those related to the structure and evolution of rifts. The Rio Grande rift is the largest such structure in North America, although it is not the most active and portions of it are poorly defined. The most promising target for deep drilling in the rift is the Socorro area. Geologic, geodetic, and seismic data indicate that this area is tectonically active. In addition, seismic data indicate the presence of magma at mid- to upper-crustal depths, in part intruded along a major rift fault. There is no young surface volcanism with which to support this conclusion or upon which to predict the composition and

condition of magma to be encountered. There are also no large active hydrothermal systems known here. Drilling this target would serve to test both the rift model of dike injection along extensional fault structures and the use of seismic data to delineate magma bodies.

The Valles Caldera represents an outstanding hydrothermal and magmatic drilling target. The target is well defined from the standpoint of geologic data, although valuable information concerning caldera evolution would be obtained from drilling. Penetrating a hot hydrothermal system is a known certainty and encountering magma or its recently crystallized equivalent is probable. In addition, structural information concerning the rift boundary and its relationship to the magma body might be obtained.

A SUMMARY OF THE GEOLOGY OF THE
ROOSEVELT HOT SPRINGS THERMAL AREA, UTAH

by

D. Emerson

ABSTRACT

Roosevelt Hot Springs discharges from a deep 260°C water-dominated geothermal reservoir that lies west of the Mineral Mountains, Utah. These mountains, which consist of a large fault-block of Precambrian basement and Paleozoic rocks intruded by Tertiary granitic rocks, sit at the east margin of the Basin and Range and west margin of the Colorado Plateau tectonic provinces. Rhyolitic domes, flows, and pyroclastics 0.8-0.5 Myr old surmount the crest of the Mineral Mountains. The young igneous activity in combination with seismic P-wave delay data suggests the presence of a silicic magma reservoir in the shallow crust. The hydrothermal system is localized along a variety of high- and low-angle fault systems that may direct fluid flow westward away from the postulated magmatic heat source. Hydrothermal alteration of granitic rocks has produced secondary mineralization that may include K-mica, K-feldspar, chlorite, calcite, and pyrite. Silica sinter is a common spring deposit. The object of a deep borehole at Roosevelt Hot Springs would be to seek evidence of the magmatic heat source and to learn how it is coupled to the hydrothermal system.

I. INTRODUCTION

The Roosevelt Hot Springs thermal area is situated on the west-central flank of the Mineral Mountains, approximately 15 km northeast of Milford, Utah. The Mineral Mountains are located near the eastern margin of the Basin and Range province. The range consists dominantly of a Tertiary granitic pluton 32 km long by 8 km wide. Rhyolitic tuffs, flows, and domes cover about 25 km² of the crest and west side of the Mineral Mountains within 5 km of the thermal area. The rhyolitic volcanism occurred between 0.8 and 0.5 Myr ago and constitutes a major Pleistocene thermal event believed to be significant to the evaluation of the area for geothermal resources (Ward et al., 1978).

Geophysical data also suggest an igneous heat source. Delayed P-wave travel times indicate a low-velocity zone beneath the Mineral Mountains at 10-25 km whereas signal-shape variations at some stations may be due to diffraction around a smaller low-velocity body at a depth of 5 km or less (Robinson and Iyer, 1979). This shallow body could be the cause of a gravity low in the central Mineral Mountains. Major swarms of earthquakes occur 30 km to the east-northeast near Cove Fort, Utah, but only minor earthquake activity occurs near the Roosevelt Hot Springs thermal area.

Thermal waters from the (now dry) spring, a seep, and the deep reservoir are dilute (ionic strength 0.1 to 0.2) sodium chloride brines with 6000 to 8000 parts per million (ppm) total dissolved solids (Parry et al., 1980).

The purpose of a deep (5-km) test hole would be to obtain information about the nature of the heat source, geologic structure, mineralogy, and fluid chemistry.

II. REGIONAL GEOLOGY

The location of Roosevelt Hot Springs and eight other known Geothermal Resource Areas (KGRAs) in Utah are shown in Fig. 14, along with the mineral belts of Utah as proposed by Hilpert and Roberts (1964) and Stokes (1968). These belts have accounted for 95% of Utah's base metal and gold production. The belts are the location of repeated Tertiary intrusive episodes and probably reflect deep-seated structural zones. The coincidence of KGRAs with the Wah Wah-Tushar Belt is impressive (Fig. 14; Nielson et al., 1978).

Figure 14 also illustrates the position of the KGRAs of Utah with respect to the trend of the Intermountain Seismic Belt (ISB) of Smith and Sbar (1974). The ISB is a belt of shallow earthquakes with focal depths of generally less than 15 km and is interpreted to be a boundary between two sub-plates of the North American Plate. The Roosevelt Hot Springs KGRA is located to the northwest of the ISB in an area where the ISB shows a clear change in orientation. At approximately the same location as the offset in the ISB, Cook et al. (1975) have shown a major linear gravity feature which they feel represents a relict transform fault.

The geology of the Mineral Mountains has been discussed by Liese (1957), Earll (1957), and Condie (1960). Petersen (1975) published a map of the Roosevelt Hot Springs area that includes much of the KGRA. Evans (1977) presented

The Mineral Mountains Pluton and highly deformed Precambrian rocks underlie much of the Mineral Mountains. At the north, the Mineral Mountains are underlain by a dark gray unfossiliferous limestone, the Prospect Mountain

Ward et al. (1978).
 a compilation of previous and some new work. Much of this discussion has been extracted from a recent study by Nielson et al. (1978) and from the summary by

Distribution of tectonic zones and KGRAs in Utah; from Nielson et al. (1978).

Fig. 14.

Quartzite, and the Pioche Formation, all of Cambrian age (Liese, 1957). Several outcrop areas of the Indianola Formation, a conglomerate of Cretaceous age, overlie the Cambrian section.

The southern portion of the Mineral Mountains, the Bradshaw Mountain area, contains Precambrian metamorphic rocks which are overlain by lower Paleozoic limestones and dolomites, Mississippian limestones of the Topache Formation, the Coconino and Kaibab Formations of Permian age, and Tertiary volcanics of andesitic to latitic composition (Earll, 1957). Most of the mining activity in the range is confined to the Bradshaw Mountain area where gold, silver, lead, copper, and tungsten have been produced from contact metamorphic deposits and associated veins.

The geology of the Roosevelt Hot Springs KGRA is characterized by meta-sedimentary and plutonic rocks of Precambrian age, intrusive rocks of Tertiary age, and flows, pyroclastics, and domes of Pleistocene age. Siliceous sinter and silica-cemented alluvium represent recent hydrothermal activity (Fig. 15).

III. REGIONAL TECTONICS

The dominant structural features of this area are those of the Basin and Range province. The Mineral Mountains and Milford Valley are an example of Tertiary and Quaternary tensional horst-graben structure. Another prominent, but older structural feature in this area is overthrusting and folding, which took place during the Sevier orogeny of late Cretaceous age. The well-defined leading edge of the thrust sheet, which advanced from the northwest and placed Cambrian rock over younger rock, is right-laterally offset along an east-northeast-trending line which passes through the County Line fault of Ward et al (1978) in the northern Mineral Mountains (Fig. 15). This offset was designated the Black Rock Offset by Crosby (1973) who considers the scattered sedimentary exposures south of this offset as part of a "disturbed belt" in which deformation and local thrusting caused by the advancing thrust sheet accounts for the complex relationships of the exposed sedimentary sections. This disturbed belt, which encompasses the entire area of study south of the offset line, is defined as a transition zone between the undeformed strata of the Colorado plateau and the severely deformed rocks of the fold and thrust belt. The Black Rock offset also marks the apparent northern termination of an east-west belt of igneous intrusions (Butler et al., 1920, Smoker, 1972) which were probably emplaced along a major structural feature.

Fig. 15.

Generalized geologic map of the northern Mineral Mountains, Utah. Quaternary rhyolites are stippled (Ward et al., 1978).

IV. IGNEOUS ACTIVITY

The Mineral Mountains pluton is the largest in Utah (approximately 250 km²) and is no older than 35 Myr (Lipman et al., 1977). The Tertiary pluton, which comprises most of the map area, is composed of eight major phases. The relative ages of the phases have been determined on the basis of crosscutting relationships where possible. Intrusive rocks in the

San Francisco and Wah Wah Mountains, to the west, yield dates of 20 to 23 Myr for quartz monzonite rocks and 27 to 29 Myr for granodiorite rocks (Lemmon et al., 1973). The nonfoliated rocks in the Mineral Mountains are assumed to be of similar ages. A thermal event about ten million years ago has reset biotite dates.

The eight major phases of the batholith are: diorite breccia (Tdb), biotite diorite (Td), quartz monzonite (Tqm), porphyritic quartz monzonite (Ti), biotite granite (Tbg), syenite (Ts), leucocratic granite (Tg), and fine-grained granite (Tgr). Dikes of microdiorite and diabase have intruded structures in the contact zone between Precambrian and Tertiary rocks in the KGRA. Three groups of porphyritic rhyolite dikes have intruded the range (Sibbett and Nielson, 1980).

The Mineral Mountains area has been the site of repeated volcanism. Mid-Tertiary volcanic activity produced calc-alkalic lavas that are exposed on the south flank of the Mineral Mountains. On the western flank of the Mineral Mountains, 8.0 Myr old rhyolite that overlies granitic alluvium derived from the Mineral Mountain pluton is exposed in Corral Canyon. Basalt dated at 7.6 Myr occurs on the southern flank of the Mineral Mountains.

The youngest episode of volcanism began about 0.8 Myr ago with the eruption of two rhyolite flows from vents located about 4 km east of the present near-surface thermal activity. These flows, along Bailey Ridge and Wildhorse Canyon, are about 3 km in length and 80 m thick. The rhyolite is almost entirely glass containing less than 1% phenocrysts of alkali feldspar, biotite, and Fe-Ti oxides. These flows have reversed magnetic polarities.

Subsequent activity from about 0.6 to 0.5 Myr ago produced at least ten rhyolite domes and small flows of rhyolite distributed over 15 km along the crest and western flank of the Mineral Mountains. The domes range from about 0.3 to 1 km in diameter and are up to 250 m high. On many of the domes an original frothy perlite carapace is still present. The domes exhibit steeply dipping flow layering and ramp structures which are not present in the more fluid earlier lava flows. The formation of domes was preceded by pyroclastic eruptions which produced air-fall and ash-flow tuffs. The dome-forming rhyolites contain up to 10% phenocrysts of plagioclase and alkali feldspar, quartz, biotite, Fe-Ti oxides, sphene, zircon, apatite, and allanite. Topaz occurs in lithophysae in crystalline rhyolite. The ash deposits and domes have normal magnetic polarities.

Representative chemical analyses indicate that the Quaternary flows and domes are high silica rhyolites (76.5%) and contain over 9% total alkalis. There are chemical differences between the two magma types; the earlier crystal-poor flows contain relatively more potassium, titanium, iron, calcium, barium, and strontium, whereas the crystal-rich domal rhyolites contain relatively more magnesium, manganese, sodium, fluorine, niobium, and rubidium. The Tertiary rhyolite contains less silica and more calcium, and is strongly enriched in strontium and barium compared to both varieties of Quaternary lavas.

Quaternary basalt was erupted from three vents on the northeast flank of the Mineral Mountains, and flows from the extensive Cove Fort basaltic-andesite field lap against the Mineral Mountains on the east.

Pre-eruption magma temperatures have been determined petrologically using both the iron-titanium oxide and the two-feldspar thermometers. Temperatures range from a high of 785°C in the flows to a low of 650°C in the domes. These temperatures suggest that the magmas contained substantial water and fluorine. Water fugacities calculated for the flows and domes are 3.0 kb and 0.4 kb, respectively (Nash and Evans, 1977).

The chemical and mineralogical data indicate that the dome-forming magma may have been derived from the earlier magma (which gave rise to the flows) by the fractionation of feldspar. The evidence does not preclude the separate generation of each magma batch, or alternatively, derivation of one from the other by chemical gradients as postulated for the Long Valley, California magma system (Hildreth, 1977). The striking chemical similarity of all the domes strongly suggests that they were derived from the same magma batch between 0.6 and 0.5 Myr.

V. HYDROTHERMAL SYSTEM

The geothermal system at Roosevelt Hot Springs KGRA is controlled by structures cutting plutonic and metamorphic rocks of Tertiary and Precambrian age (Fig. 16). A major low-angle normal fault, mapped along the western margin of the Mineral Mountains (Nielson et al., 1978; 1979), is characterized by intense cataclasis of the crystalline country rock. Offset (dip-slip) has been determined to be approximately 600 m in a westerly direction. The hanging wall of this fault is intensely brecciated where friction between large blocks has produced steeply dipping mylonite zones. Both the steep- and shallow-dipping

Fig. 16.
Generalized east-west geologic cross section through Roosevelt Hot Springs thermal area; from Nielson et al., 1978.

mylonite zones have been altered and silicified to produce an impermeable but brittle rock. Strong jointing with increased permeability is often found adjacent to the mylonite zones. Permeability in the upper levels of the geothermal field occurs from the intersection of the mylonite zones formed during denudation faulting with the steeply dipping normal faults similar to the Opal Mound Fault.

Geothermal fluids are conveyed from depth along the Negro Mag Fault (Hot Springs fault of Ward et al., 1978) as well as the Opal Mound Fault and parallel structures. These fluids enter shallow reservoirs, in the area of drill hole 72-16 (Fig. 15), which result from the increased structural permeability in the hanging wall of the denudation fault. Also, within this environment it is possible that geothermal fluids may be channeled laterally along denudation faults and subsidiary structures such that surface and near-surface manifestations of geothermal activity are laterally displaced from deeper reservoirs.

Hot spring deposits consist of siliceous sinter and minor sulfur. Thin horizontally bedded, dense, varicolored opaline sinter produced as a result of primary deposition of silica on broad spring aprons occurs in the Opal Mound

area, where laminated, knobby, and colloform opal also occur. Laminations dip steeply to vertically within old spring vents exposed along the Opal Mound fault.

Coarsely crystalline granite grading to quartz monzonite of Tertiary age, and alluvium have been hydrothermally altered in the Roosevelt Hot Springs thermal area. The alluvium consists of mineral and rock fragments derived from granite and volcanic rocks of the Mineral Range which have been cemented by opal and chalcidony. Feldspars have been altered by acid-sulfate water to alunite, opal, and hematite. Native sulfur occurs as very fine to coarse euhedral to anhedral intergranular crystals. Micro-crystalline sulfur is intergrown with alunite. Cubic pseudomorphs of hematite after pyrite are also present.

Hydrothermal alteration is closely associated with fractures in the Mineral Mountains pluton to a depth of 2 km in Thermal Power Co. well Utah State 14-2 (Fig. 15). Clay minerals, montmorillonite, and mixed layer clays, commonly found only near the surface near the Opal Mound fault, occur to the depth of 500 m in well 14-2 with K-mica, K-feldspar, pyrite, calcite, and limonite. The deeper alteration assemblage from 500 m to 2 km consists of K-mica, chlorite, calcite, K-feldspar, and pyrite.

Anomalous concentrations of mercury, arsenic, and lead are associated with the altered rocks. Mercury anomalies as high as 3 ppm are localized over faults in surface rocks. Maximum arsenic in surface rocks is 2000 ppm near the opal mound, and 430 ppm in altered rocks in drill holes. Maximum lead content of altered rocks is 400 ppm in altered alluvium in one drill hole. The thermal waters are relatively dilute (ionic strength = 0.1 to 0.2) sodium-chloride brines. Sulfate concentrations vary between 48 and 120 mg/l and total dissolved solids are approximately 7000 mg/l. Chemical differences exist between surface and deep thermal fluid, consisting principally of higher Mg^{++} , Ca^{++} , and SO_4^{--} and lower Na^+ , K^+ , and SiO_2 in surface relative to deep waters. These differences presumably reflect progressive leaching of Mg and Ca by ascending thermal fluids, oxidation of H_2S or admixture of oxidized, SO_4^{--} rich, surface waters, and flashing and cooling with subsequent precipitation of opal. The Roosevelt Hot Springs geothermal fluids are chemically similar to New Zealand geothermal fluids.

Application of the Na-K-Ca and SiO_2 thermometers (Fournier and Truesdell, 1974) to the seep and the deep geothermal fluid indicates deep water

temperatures of 241° and 286°C, respectively, which agree well with deep down-hole measurements. The Na-K-Ca wall-rock equilibration temperature on the Roosevelt seep sample is one of the highest calculated subsurface temperatures in Utah. This high temperature and the presence of extensive surface opal deposits first suggested a viable geothermal resource at Roosevelt Hot Springs.

VI. PROBLEMS AND CONCLUSIONS

The information about the Roosevelt Hot Springs thermal area has been obtained from extensive surface studies and several drill holes, one to a depth of 2300 m. However, little is known about the deep internal characteristics of the geothermal or magmatic systems. The igneous heat source indicated beneath the Mineral Mountains is postulated from seismic and gravity information but the P-wave delay data provide only a tenuous suggestion of partial melt. An intense fracture zone would be another possible explanation.

Additional studies are in progress but none will provide the direct information that would result from a deep hole into the region of the heat source. An existing open hole, the 2100 m deep LASL C/T-2, Phillips 9-1, is available for borehole measurements and instrument calibration. Cased to 1280 m, this hole is fluid filled and has a maximum temperature of 220°C. Getty Oil's 52-21 well that was drilled to about the same depth, may also be available. There is industrial interest in a cooperative test hole to determine what is beneath the geothermal resource. This would have to be a hole dedicated from the surface down and planned to obtain information about the nature of the heat source, geologic structure, mineralogy, and fluid chemistry. To be useful, it would probably have to be at least 4-5 km deep. Experiments within the wet steam production wells or deepening existing holes is probably not feasible.

THE GEOLOGIC SETTING OF THE SALTON TROUGH

by

Harold Wollenberg, Steve Vonder Haar, and Neil Crow

ABSTRACT

The Salton Trough is a rift valley, the landward extension of the Gulf of California. The system of right-lateral, strike-slip transform faults and cross faults, which offsets the East Pacific Rise in the Gulf, also extends on-shore and appears to control the locus of active hydrothermal systems in the Mexicali and Imperial valleys. The crystalline basement underlying the trough, composed predominantly of Mesozoic granitic rock, is overlain by up to 6 km of sedimentary rocks, primarily lacustrine deposits and deltaic sediments associated with the ancestral Colorado River. Pleistocene volcanic activity was superimposed on the sedimentary sequence, with present-day surface manifestations in the form of obsidian-rich rhyolitic domes at the south end of the Salton Sea and the rhyodacitic cone of the Cerro Prieto volcano. The Cerro Prieto geothermal field, presently producing 150 MW (electrical), and the Salton Sea geothermal field of high economic potential are two prominent hydrothermal systems currently under study by publicly supported projects. Information is being obtained at each site on its thermal, hydrologic, and lithologic settings to depths of several kilometers. Use of existing drill holes or deeper drilling for scientific purposes will permit determination of the sources of heat for the geothermal systems, be they dike swarms, magma chambers, and/or deep hydrologic circulation into zones of very high conductive heat flow. Most importantly, information from such drill holes will considerably advance our knowledge of the thermal regimes associated with this region of continental-oceanic transition.

Currently active hydrothermal systems of the Salton Trough, a tectonically active region extending north-northwestward from the Gulf of California into southeastern California, will be emphasized. As examples of geothermal systems perhaps characteristic of the Salton Trough, the Cerro Prieto geothermal field in northern Baja California and the Salton Sea field at the south end of the lake of that name, will be described in some detail. The locations

of these fields, and the other known geothermal resource areas Brawley, East Mesa, Dunes, and Glamis, are shown on the map, Fig. 17.

I. REGIONAL GEOLOGIC SETTING

The most recent comprehensive description of the regional setting of the Salton Trough is that by Elders (1979) (see also Fig. 18). The trough is considered to be a rift valley, the landward extension of the Gulf of California into North America. Within this rift valley sedimentation has nearly kept pace with tectonic activity. The lithologic and tectonic settings will be described briefly in this section.

A. Lithology

The oldest sedimentary rocks in the Salton Trough are of Miocene age, represent non-marine depositional environments, and rest on a crystalline basement composed of Mesozoic granitic rocks which intruded Paleozoic and Precambrian sedimentary rocks. This basement may also contain Miocene and younger volcanic units, and metamorphic rocks. The lithology of the Late Miocene to early Pliocene sedimentary rocks indicates that there was a marine incursion

Fig. 17.
Location map, Salton Trough.

XBL 801-6718

Fig. 18.
Salton Trough index map showing Imperial and Mexicali Valleys.

into the well-defined structural trough at that time. The presence of an ancestral Colorado River at least 5 Myr ago is indicated by the lithology of the Imperial Formation of Pliocene age. The Pleistocene was characterized by alternating lacustrine and deltaic sedimentation in the central portion of the trough concurrent with deposition of conglomerates on the western margin of the basin.

The formation of the delta of Colorado River across the north end of the gulf isolated the Imperial Valley (Fig. 18). During times of flooding, the Colorado River changed course, occasionally emptying into the landlocked basin. This resulted in the formation of lakes and changing patterns of sedimentation. The deltaic deposits consist of fluviatile and lacustrine interbedded sands, silts, clays, occasional evaporites, and pebble conglomerates. In the central portion of the southern part of the basin in the Cerro Prieto area, their aggregate thickness exceeds 3 km, and wells have penetrated up to 4 km of Pleis-

tocene sediments in the Imperial Valley. Depth to basement rocks in the northern portion of the Salton Trough, near the Salton Sea, is estimated to be 6 km.

Pleistocene volcanic activity has been superimposed on the sedimentary rocks (Fig. 19). In the Salton Trough the volcanic activity is manifested in two localities: 1) by rhyolitic, obsidian-rich domes at the southern margin of the Salton Sea, and 2) by the rhyodacite cone of the Cerro Prieto volcano. A single age determination on a sample from Obsidian Butte, the westernmost of

Gross tectonic environment of the Salton Trough. The Pacific Coast of North America is dominated by transform fault systems, which connect the spreading centers of the East Pacific Rise to those of the Gorda Ridge. Also shown are pull-apart basins between en echelon fault segments in the Gulf of California. Oceanic fracture zones (FZ) and continental faults (F) are solid black lines, dashed where uncertain. Other abbreviations: SAF = San Andreas Fault; EF = Elsinore Fault; SJF = San Jacinto Fault; ABF = Agua Blanca Fault; SRF = Santa Rosalia Fault; W = Wagner Basin; D = Delfin Basin;

▲ = Holocene volcanoes; B = Salton Buttes; C = Cerro Prieto; and R = Revillagigedo. (Source: Elders, *et al.*, 1972.)

Fig. 19.

Gross tectonic environment of the Salton Trough (Fig. 4 from Palmer *et al.*, 1975).

the domes, gave an age of approximately 60 000 years (Muffler and White, 1969). To date, attempts at radiometrically dating the Cerro Prieto rhyodacite have been unsuccessful, though its normal magnetic polarity indicates that it was extruded within the past 700 000 years. Recent studies of the remanent magnetism of the Cerro Prieto rhyodacite (deBoer, 1979) indicated that pole positions correspond to the excursion paths of the Gothenburg magnetic event (≈ 10 000 years b.p.) and the Blake event (≈ 100 000 years b.p.). deBoer thus concludes that Cerro Prieto volcanism "...was initiated shortly before the Blake event and that it continued periodically until the Gothenburg event, over a period of some 100 000 years." Preliminary strontium isotope and other dating investigations (W. Elders, personal communication, 1980) suggest that the Cerro Prieto hydrothermal events are very young, perhaps 10 000 years b.p.

B. Tectonics

The regional tectonic environment of the Salton Trough is dominated by a transform fault system which offsets the crest of the East Pacific Rise progressively northward through the Gulf of California. The transform faults are characterized by active right-lateral strike-slip faulting. As shown in Figures 19 and 20, "pull-apart basins" or spreading centers are spaced along the Gulf, with the northernmost, the Waggoner Basin, located close to the mouth of the Colorado River (Fig. 19). Elders (1979) pointed out that the highest temperature geothermal fields in the Salton Trough--Salton Sea (365°C), Cerro Prieto (350°C), and Brawley (295°C)--are located in young pull-apart zones. This concept, illustrated in Fig. 20, has been supported by results of geodetic surveys and seismic observations.

The principal faults in the region generally strike northwestward (Fig. 20) and exhibit predominantly right-lateral strike-slip motion, consistent with the strike and general direction of motion of the San Andreas system. In some cases, vertical offsets of tens of centimeters have been associated with earthquakes in the Imperial Valley. A good example is in the Mesquite Lake area between El Centro and Brawley where vertical offsets on the Imperial and Brawley faults have formed a graben, activated in the 1940 Imperial Valley earthquake and reactivated in the 1973-1976 Brawley swarm of earthquakes (Hill, 1977), and more recently in the earthquakes of October 1979.

The Brawley earthquake swarms were shown by Johnson (1979) to occur on transverse structures connecting the Brawley and Imperial faults. Johnson

Possible relationship between pull-apart basins and strike-slip faulting in the Salton Trough. Postulated "spreading centers" or tensional zones, young volcanics, geothermal areas, and zones of intense folding and compression in Tertiary sediments are indicated.

Fig. 20.

Pull-apart basins and strike-slip faulting in the Salton Trough (Fig. 6 from Palmer et al., 1975).

proposed that the swarms resulted from right-lateral aseismic creep within the sub-alluvial bedrock, associated with changes in pore pressure in the deep hydrologic system. Hill (1977) suggested alternatively that the swarms were associated with dikes being emplaced as linear bodies parallel to the transverse structures.

Research in progress by G. Fuis (USGS, Menlo Park) and his colleagues, based on extensive seismic refraction in the Imperial Valley, should provide some answers for the regional deep structure. For example, the questions of the thickness of sediments, the presence of a metamorphic zone near 5 km, and the possibility of oceanic type crust at 6- to 12-km depths are being addressed.

The Salton Trough has long been a subsiding feature, and the thick sediment accumulation (as much as 6 km) since the late Miocene suggests the magnitude of this motion. Lofgren (1978; and reports in progress) summarizes the results of precision vertical elevation fluctuations from a regional leveling network. His maps indicate an active zone corresponding roughly with the Brawley seismic zone; a study is underway (N. Crow, LLL, in preparation) to document this relationship.

II. THE CERRO PRIETO GEOTHERMAL FIELD

The Cerro Prieto geothermal field is located in northern Baja California, ≈ 30 km south of Mexicali and ≈ 5 km south-southeast of the Cerro Prieto Volcano. The surface layout of the field is shown in Fig. 21. Development of the field was begun in the late 1960's by the Comision Federal de Electricidad on the basis of the presence of abundant surface manifestations (hot springs and fumaroles) and hot water encountered in relatively shallow agricultural wells. Currently, the field encompasses more than 60 wells, producing from depths ranging from 1.5 to over 3 km (Alonso et al., 1979). The field is liquid-dominated and temperatures at depth range from 220° to over 350°C . Subsurface exploration indicates that the field extends generally eastward and southeastward from the currently producing zone, with production depths expected to increase to over 3 km. Electrical production of the field is currently 150 MW. With the addition of a second plant the capacity will be enlarged to 370 MW by 1985.

A. Geologic Setting

The geologic setting of the Cerro Prieto area is dominated by the thick sequence of late Cenozoic deltaic and lacustrine sedimentary rocks, transected by the north-northwestward-trending strike-slip faults and by northeast striking cross faults. Geophysical surveys indicate that the Cerro Prieto Volcano

Fig. 21.

Surface layout of the Cerro Prieto field (Fig. 1 in Alonso et al., 1979).

has little if any effect on the geophysical patterns associated with the geothermal field.

1. Structure

An idealized east-west geologic section through the field by Puente Cruz and de la Pena (1979) is shown in Fig. 22. Though only a few wells have penetrated the basement rocks, their intersections indicate a general deepening of the sedimentary section from west to east, with fault blocks bounded by the northwesterly-striking faults, displaced progressively downward to the east. Seismic refraction surveys in the vicinity of the geothermal field indicate that east of the Cerro Prieto Fault, the depth to basement is of the order of 5 km. West of the fault the basement refractor (5700 m/s) is at a depth of 2 to 3 km.

XBL 798-10916

Fig. 22.

Idealized east-west geologic cross-section through the Cerro Prieto area (Fig. 9 from Puente Cruz and de la Pena, 1979).

The structural framework of the field has been studied by Vonder Haar and Howard (1980). This framework, derived from interpretation of subsurface data from well logs, is illustrated in Fig. 23. The currently producing area of the field is located between the Cerro Prieto fault and a fault roughly paralleling it approximately 3 km to the west. Vonder Haar and Howard point out that the high productivity of well M-103 (Alonso et al., 1979) may be due to its proximity to the intersection of the Cerro Prieto Fault with the north-northeast-striking set of faults. The intersection furnishes a zone of relatively high permeability, serving as a preferential conduit for convective circulation of geothermal fluids.

Based primarily on well-log correlations, Lyons and van de Kamp (1980) recognized three principal types of faults in the sedimentary rocks: 1) older faults offsetting the deeper parts of the sedimentary section, 2) reactivated older faults, and 3) young faults which offset the entire section. Though only the dip-slip component is evident from well-log correlations, there may also be significant lateral slip in some cases. Vertical offsets range from a few hundred meters to nearly a kilometer, as shown in diagrams by Abril and Noble (1979) and Prian (1979).

Fig. 23.
Structural setting of the Cerro Prieto field (Fig. 5 in Vonder Haar and Howard, 1980, in preparation).

2. Lithologic Setting

The lithology of the Cerro Prieto Field, based primarily on well-log correlations, was described by Puente Cruz and de la Pena (1979) and by Abril and Noble (1979). The stratigraphic section of Cerro Prieto was divided into three broad units: Unconsolidated sediments (silts, clays, sands), consolidated sandstones and shales, and granodioritic basement rocks. Within the consolidated sedimentary rocks two principal reservoir horizons were recognized: an upper reservoir 200-300 m thick, from which most of the present production from the field is derived, and a lower reservoir horizon where temperatures reach 350°C. The two horizons are separated in some locations by ≈50 m of relatively impermeable lutitic material.

This preliminary assessment of the field's lithology was more recently refined by Lyons and van de Kamp (1980). Predominantly on the basis of well log analyses, they recognized five classes of lithofacies, each with characteristic lithology and apparent thickness. Each class is represented in the aforementioned broad lithologic units. As would be expected, production is limited to the thicker, sandier classes, representative of a delta plain depositional environment. Lyons and van de Kamp (1980) proposed that the boundary between the unconsolidated and consolidated sedimentary rocks is not a stratigraphic marker horizon, but rather an induration boundary in response to post-depositional alteration by hydrothermal fluids.

From petrographic and mineralogic analyses of well cuttings, four zones of alteration were recognized by Elders et al. (1980). In order of increasing threshold temperature these are: 1) a diagenetic zone, 2) an illite-chlorite zone ($>150^{\circ}\text{C}$), 3) a calc-aluminum silicate zone ($>230^{\circ}\text{C}$), and 4) a biotite zone ($>325^{\circ}\text{C}$). Vertical profile and block diagrams of depths to the first appearance of diagnostic alteration minerals (Figs. 24 and 25) indicate the temperature distributions within the field. A block diagram of the "topo-

Fig. 24.
Distribution of mineral zones in sandstones.

XBL 805-7073

Fig. 25.

Block diagram of the "topographic surface" of the first appearance of 5% epidote in sandstone ($\approx 230^{\circ}\text{C}$), and an upper densified zone ($\approx 180^{\circ}\text{C}$) (Data based on Elders et al., 1980).

graphic surface" of the occurrence of 5% epidote by weight ($230\text{--}250^{\circ}\text{C}$) (Fig. 25) shows a wedge-shaped high at a depth of ≈ 1 km in the vicinity of the producing field, deepening to over 2 km in wells to the east and south-east. The configuration of the alteration-mineral horizons generally conforms to the dome-like pattern of relatively high density and high electrical resistivity associated with the producing field, discerned by surface geophysical surveys.

The authigenic mineral assemblages and light stable isotope patterns indicate (Elders et al., 1980) a thermal plume elongated in a NW-SE direction and dipping at 45° to the NE. This plume strongly suggests discharge of fluid to the SW and recharge from the NE. Fractures in the reser-

voir rocks often appear to be sealed by hydrothermal mineralization. Therefore, though fracture permeability may play a role, Lyons and van de Kamp (1980) consider that secondary matrix porosity due to the solution effects of the geothermal fluids in the sandstones is a major factor in providing reservoir permeability. This is corroborated by downhole geophysical logs, petrographic observations of thin sections of cores from the production zone, and scanning electron microphotographs.

B. Hydrologic System

The most direct evidence for the origin of the geothermal waters at Cerro Prieto and their circulation within the geothermal system is provided by geochemical studies, summarized recently by Truesdell et al., (1980). The deuterium concentration of brines from the field is similar to that of present day Colorado River water, but distinctly different from local rain water, sea

water, and water from the Salton Sea (Fig. 26). On the other hand, the Cl/Br ratio (300-400) is similar to that of coastal sea water, but considerably lower than the ratio in Colorado River and Salton Sea water (≈ 1500). This suggests a possible Colorado River origin of the Cerro Prieto water and a seawater origin of its dissolved salts. To reconcile this, Truesdell et al. (1980) propose that sea water constituents were concentrated by solar evaporation in coastal lagoons. The ion-rich water was incorporated into deltaic sediments of the Mexicali Valley, and subsequently diluted (≈ 11 times) by infiltrating Colorado River water to produce the salinity, Cl/Br ratio and deuterium concentration currently observed in Cerro Prieto geothermal waters.

The pathways of fluids into and within the Cerro Prieto field were inferred from the Na-K-Ca index (Manon et al., 1979). The indices of waters from the producing wells indicate that cold waters of relatively low salinity are probably recharging the aquifers in the northern and western portions of the field. This recharge is substantiated by the distribution of the chloride content in waters from producing wells. Comparison of chloride content and oxygen-isotope ratios of waters from wells measured in 1973-1974 with contents

Fig. 26.

Hydrogen- and oxygen-isotope concentrations of surface waters, irrigation well waters and Cerro Prieto geothermal waters (Fig. 1 from Truesdell et al., 1979).

analyzed in 1977-1978 (Truesdell et al., 1979) suggests that drawdown of an upper-producing aquifer is occurring in response to production, causing waters lower in ^{18}O and Cl to dilute waters richer in these constituents in the south-central portion of the field.

It appeared to Truesdell et al. (1980) that two brines are present in the production aquifer; one with 10 000 mg/kg chloride and temperatures of 270-295°C, and the other with 8000 mg/kg Cl and temperatures between 260° and 280°C. The latter brine, whose temperature was probably considerably lower than 260°C, was most likely drawn down into the production aquifer and heated by contact with production-aquifer rocks and minerals.

C. Cerro Prieto Summary

The Cerro Prieto geothermal field is localized in a zone of crustal spreading, most likely at an offset of the landward extension of the East Pacific Rise. The field lies ≈ 5 km southeast of the rhyodacitic Cerro Prieto Volcano, whose maximum age has been estimated at 110 000 years. The present electrical capacity of the Cerro Prieto geothermal field is 150 MW, based on production of hot water from 55 wells. Expansion of the well field to the east and southeast will increase electrical production to 370 MW over the next five years. Temperatures in the wells range from 220 to nearly 350°C at production depths from 1800 to nearly 3000 m, with the hotter, deeper zones located in the east and southeastern portions of the field. Two producing horizons, characterized by their chemistries and temperatures, are composed predominantly of sandstone, but also contain abundant interbedded shale. Reservoir permeability is afforded by fractures, combined with secondary porosity of the sandstone resulting from the solution effects of the circulating hydrothermal fluids. The geothermal reservoir is recharged by waters primarily from the northeast and east. The waters are partly of Colorado River origin and partly derived from sea water whose chemical constituents were concentrated by solar evaporation in coastal lagoons.

Studies to date have not disclosed the nature of the heat source for the Cerro Prieto field. It is still questionable whether the field is perched above a discrete magma reservoir at relatively shallow depth or whether it results just from hydrologic circulation into a deep, permeable, fractured zone at depths where temperatures reach over 350°C because of very high conductive heat flow. In either case it is most likely that the heat source is

associated with one of several zones of crustal spreading within the Salton Trough.

III. THE SALTON SEA GEOTHERMAL FIELD

The Salton Sea field, currently the northernmost of the areas of high geothermal potential in the Imperial Valley, occupies 46 km^2 near the south-east shore of the Salton Sea (Figs. 17 and 27). The earliest wells were drilled for the production of carbon dioxide in the vicinity of a thermal

Fig. 27.
Well locations in the Salton Sea geothermal field (Tewhey, 1977).

spring area northeast of the present field. In his compilation of characteristics of the field's geothermal wells, Palmer (1975) listed eight owners controlling 24 wells. Of these wells, 18 have been drilled since 1958; their depths range from 500 to 2500 m. Hot water (150 to over 300°C) was usually encountered at depths between 300 and 1500 m. The water is very saline, containing 20 to 30% by weight of solids (Palmer et al., 1975). Primarily because of problems associated with the high salinity, no significant amounts of electric power have been, or are currently being produced from the field. Towse (1975) estimated that if conversion technology were developed to solve the salinity problem, the identified geothermal electrical resource is 250 MWe (20 years equivalent) with an additional 150 MWe expected but yet undiscovered. Pilot plants to test the recovery of valuable elements from the high-salinity brines, as well as to examine various methods of electrical production, have been operated at times over the past two decades.

A. Geologic Setting

As with the Cerro Prieto field, the geothermal system of the Salton Sea field is associated with a thick sequence of Colorado River deltaic sediments, transected and bounded by northwest-striking transform faults. The proximity of the rhyolitic Obsidian Buttes to the Salton Sea field is somewhat similar to the presence of the rhyodacite Cerro Prieto volcano near the Cerro Prieto geothermal field.

1. Structure

The structural setting is illustrated by a cross section of the Salton Trough and the Salton Sea geothermal field, presented by Tewhey (1977) and reproduced here as Fig. 28. As shown on the cross section and a simplified geologic map (Fig. 29), the field appears to be bounded on the northeast by the Calipatria Fault and on the southwest by the nearly parallel Brawley Fault. Electrical resistivity surveys by Meidav et al. (1976) suggested the presence of northeasterly striking cross faults whose intersections with en-echelon faults of the Brawley-Calipatria system may have furnished fracture permeability to localize the Obsidian Buttes and the geothermal system. The cross section (Fig. 28) also shows that no wells have penetrated the contact with sub-alluvial basement rocks, whose depth, based on geologic and geophysical evidence, is estimated to be of the order of 6 km.

Fig. 28.

Cross section of the Salton Trough and the Salton Sea geothermal field (Tewhey, 1977).

Fig. 29.

Location of the Salton Sea field and nearby faults in the Imperial Valley (Tewhey, 1977).

2. Lithologic setting

The most detailed description of the lithology of the Salton Sea field is that by Tewhey (1977) which is based on examination of drill cuttings and cores from three wells, and covers a depth range from the surface to over 1200 m. Three main sedimentary zones were noted: 1) relatively impermeable cap rock extending from the surface to 350 m, 2) reservoir rock, relatively unaltered by hydrothermal fluid, from 350 to 900 m, and 3) hydrothermally altered reservoir rock, below 900 m.

The cap rock is predominantly a series of partially consolidated clays, silts, and evaporites. The uppermost 200 m of the cap rock consists of unconsolidated silt, sand, and gravel. Below 200 m the cap rock is predominantly a low-permeability assemblage of anhydrite-rich evaporites in a carbonate-clay matrix. This low-permeability zone effectively forms the cap on the underlying reservoir rocks. Petrographic examinations indicated to Tewhey (1977) that mineral deposition from hydrothermal fluids circulating in microcracks and fractures of the cap rock have sealed off essentially all thermal spring activity.

The reservoir rocks underlying the cap rock to depths of 900-1000 m are only slightly altered, so that their porosity and permeability are essentially unaffected by the alteration. The unaltered sequence comprises well-indurated shales, siltstones and sandstones, the latter primarily of quartz and feldspar grains cemented with calcite and silica. Pyrite is present within the entire sequence of cap rock and reservoir rock, in amounts ranging from a few tenths of a percent to over one percent. Tewhey (1977) considers pyrite in the cap rock to be of diagenetic origin, while its presence as well-formed crystals in the reservoir rocks attests to its hydrothermal origin. Small amounts of chlorite and illite, also considered to be the results of hydrothermal alteration, are present in the relatively unaltered reservoir rock.

At depths below 900-1000 m, hydrothermal alteration has profoundly affected the porosity and permeability of the reservoir rocks. The change in the reservoir rocks from moderate to relatively low permeability roughly corresponds with the first appearance of epidote. This is illustrated by Fig. 30, which compares contours of the top of the alteration zone as determined by electric logs with contours of depth to the first appearance of epidote. The substantial decrease in porosity with depth in the reservoir rocks, from 16-24% at ~800 m to 5 to 10% at 1500-1700 m, is considered by Tewhey (1977) to be

Fig. 30.
Alteration zone contours (Tewhey, 1977).

primarily the result of the hydrothermal alteration. Therefore, that porosity and permeability that is present in the hydrothermally altered portion of the reservoir rocks is primarily due to intersecting fractures.

B. Hydrothermal Systems

The sources of water for the circulating hydrothermal system may be disclosed by the chemistry of some well fluids. The Cl/Br ratios of water from wells in the northern part of the field, ≈ 1300 (Palmer, 1975), are similar to those of Colorado River and Salton Sea water, ≈ 1500 (Truesdell et al., 1980), while a considerably higher ratio, 6200, occurs in water from the Sinclair No. 4 well in the southern portion of the field. The lower ratios are compatible with recharge to the northern portion of the field from the Colorado River and/or the Salton Sea, while the high ratio in Sinclair No. 4 water suggests recharge from a different source or local contamination of recharging Colorado River-Salton Sea water by water very rich in chloride.

The pattern of circulation of water within the hydrothermal system is suggested by the distribution of temperature with depth. This is illustrated by a block diagram from Palmer (1975), Fig. 31. The thermal anomaly appears as a dome with temperatures to 350°C at a depth of ≈ 1000 m in its center, corresponding roughly to the position of the southeast shoreline of the Salton Sea and the Obsidian Buttes. This pattern implies a convecting system whose

Fig. 31.
Block diagram of isothermal surfaces - Salton Sea Geothermal Field (Palmer, 1975).

upward limbs may be driven by heat associated with the buttes, and whose downward limbs reflect recharge of local, very saline waters into the system. However, the pattern of subsurface circulation remains unclear, and as Palmer points out, it will be affected strongly by faults traversing the field, by patterns of sedimentation, and by the geothermally produced metamorphic zone that may act as a relatively impermeable barrier, separating shallow water from deep geothermal waters.

Elders et al. (1972) speculated on the geothermal regime underlying the Obsidian Buttes area. Various possible temperature-depth relationships are illustrated in Fig. 32, reproduced from their paper. Given the convecting

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CONCLUSIONS FOR THE CONTINENTAL SCIENTIFIC DRILLING PROGRAM

The job of choosing the first location for a deep borehole through a major magma-hydrothermal system will not be an easy one. As we have seen, all five systems reviewed in this volume are associated with young volcanism, active tectonics, and surface hydrothermal features. It is appropriate that we summarize these systems briefly and suggest the best target within each system for a deep 5-8 km borehole.

The Geysers-Clear Lake Region, CA: This thermal regime displays a great deal of diversity with respect to hydrothermal systems and also has a geophysically well-defined magmatic system. Thermal gradients are $\geq 60^{\circ}\text{C}/\text{km}$ throughout a region of at least 100 km^2 . Two primary targets can easily be chosen. A deep borehole through The Geysers vapor-dominated geothermal system could tell us how these relatively rare and economically attractive systems are formed. A second deep hole through the Clear Lake Volcanics could possibly tell us much about the relationship of hydrothermal systems to shallow magma reservoirs. It would also test the geophysical interpretations used to explore for shallow magma reservoirs.

Long Valley Caldera, CA: Long Valley possesses a large volume of young silicic volcanics and some geophysical evidence of magma at shallow levels. However, the active hydrothermal systems are of modest size and perched at high stratigraphic levels near recent faults. Thermal gradients at deep levels are not known above $37^{\circ}\text{C}/\text{km}$. The best target for a deep borehole is probably in the resurgent dome that overlies the center of postulated magma. This hole could resolve the discrepancy between the thermal gradient and other geophysical interpretations.

Rio Grande Rift, NM-CO: The Rio Grande rift is an extremely large tectonic feature having at least two possible targets. The most impressive is Valles Caldera, which has erupted huge volumes of silicic volcanics and has a well-explored 260°C hydrothermal system. However, geophysics does not clearly define a magma reservoir at shallow depths. The best location for a deep hole might be on the east margin of the hydrothermal system near Valle Grande over

the postulated center of shallow magma. This could tell us much about magmatic evolution of the caldera, the associated hydrothermal system, and possibly Rio Grande rift tectonics.

A second location in the rift could be the Socorro, NM, area where geophysics suggests shallow intrusions of probable basaltic composition. This hole might tell us much about deep tectonics in the rift. Unfortunately, there is no surface volcanism to verify intrusions at depth, nor is there evidence of associated hydrothermal systems.

Roosevelt Hot Springs, UT: The 260°C hydrothermal system at Roosevelt has been well studied, but lies to the east of the young rhyolitic eruptions of the Mineral Mountains. Geophysics does not clearly define a shallow magma reservoir. The best location for a deep hole might be on the crest of the Mineral Mountains to penetrate the postulated magma source and possibly intersect deep hydrothermal systems.

Salton Trough, CA: The Salton Trough overlies a major oceanic rift and continental transform zone and possesses the best-studied, high-temperature hydrothermal systems in the world. The effects of hydrothermal sealing up to epidote grade by thermal waters have been clearly demonstrated. Although surface volcanics are volumetrically small, drill holes have intersected young basaltic dikes at depth. Deep boreholes through either the Cerro Prieto or Salton Sea geothermal fields might tell us a great deal about processes of basalt injection into basin fill sediments of the Salton Trough and the relationship to associated hydrothermal systems.

The Continental Scientific Drilling Program specifically mentions magma hydrothermal systems as prime targets for deep boreholes to obtain valuable scientific information. A wealth of data could be obtained from any one of the five systems reviewed here.

ACKNOWLEDGMENTS

Dennis Nielson, UURI, contributed a great deal to the section on Roosevelt Hot Springs. Jamie Gardner, LASL, helped review, and Nancy Eckhoff, LASL, helped type and proof the five manuscripts of this volume. John Pasciewicz designed the cover.

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