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 km^2 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.

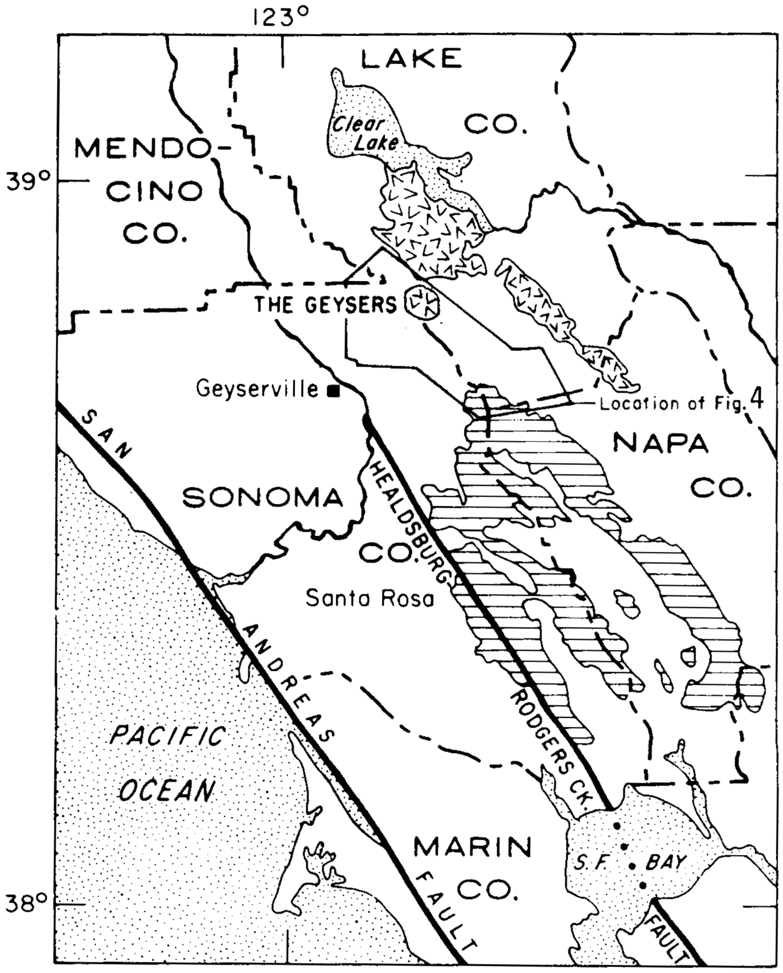

Fig. 2.
Location map of The Geysers geothermal area and late Tertiary and Quaternary volcanic rocks; McLaughlin and Stanley (1976). The V pattern indicates location of Clear Lake Volcanics; line pattern, Sonoma Volcanics. White areas are predominantly Mesozoic basement rocks.

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, particularily 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

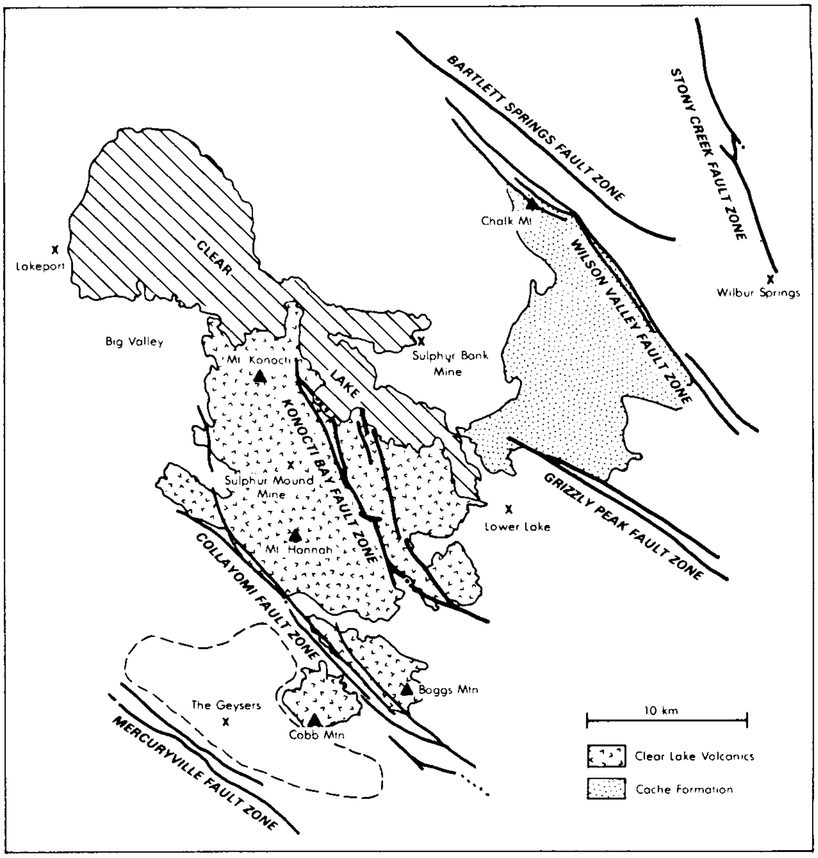

Fig. 3.
Map showing major right-lateral strike-slip fault zones of the San Andreas system in relation to The Geysers, the Clear Lake Volcanic field, and the Cache Formation. Dashed line outlines the Geysers steam field.

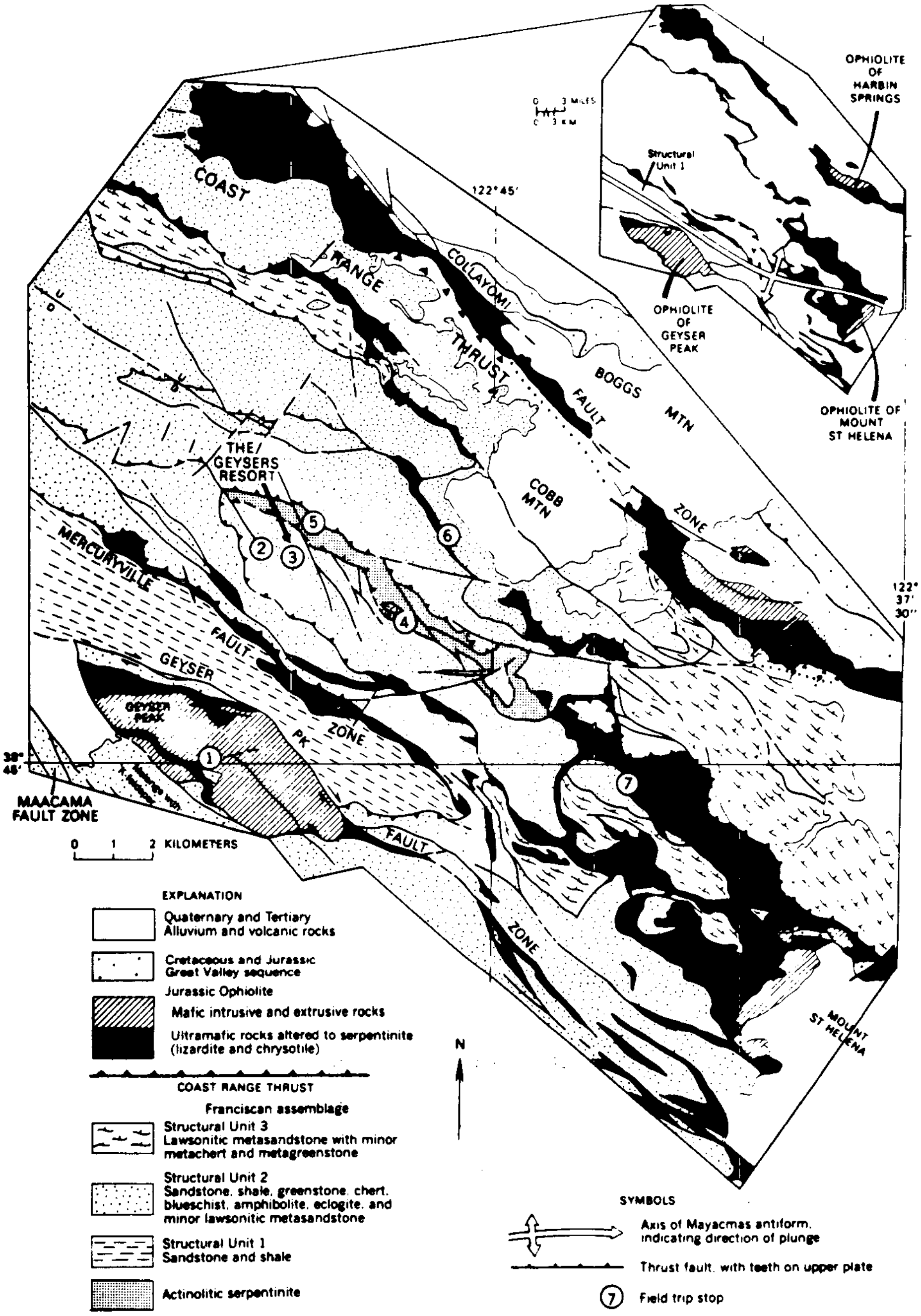

Fig. 4.
Generalized geologic map of The Geysers steam field and vicinity; McLaughlin (1977).

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). Serpentinites (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 reactiviated 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.

<u>Age Relations</u>. 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 Pesagno, 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-Pliestocene 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, volcaniclastic 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.

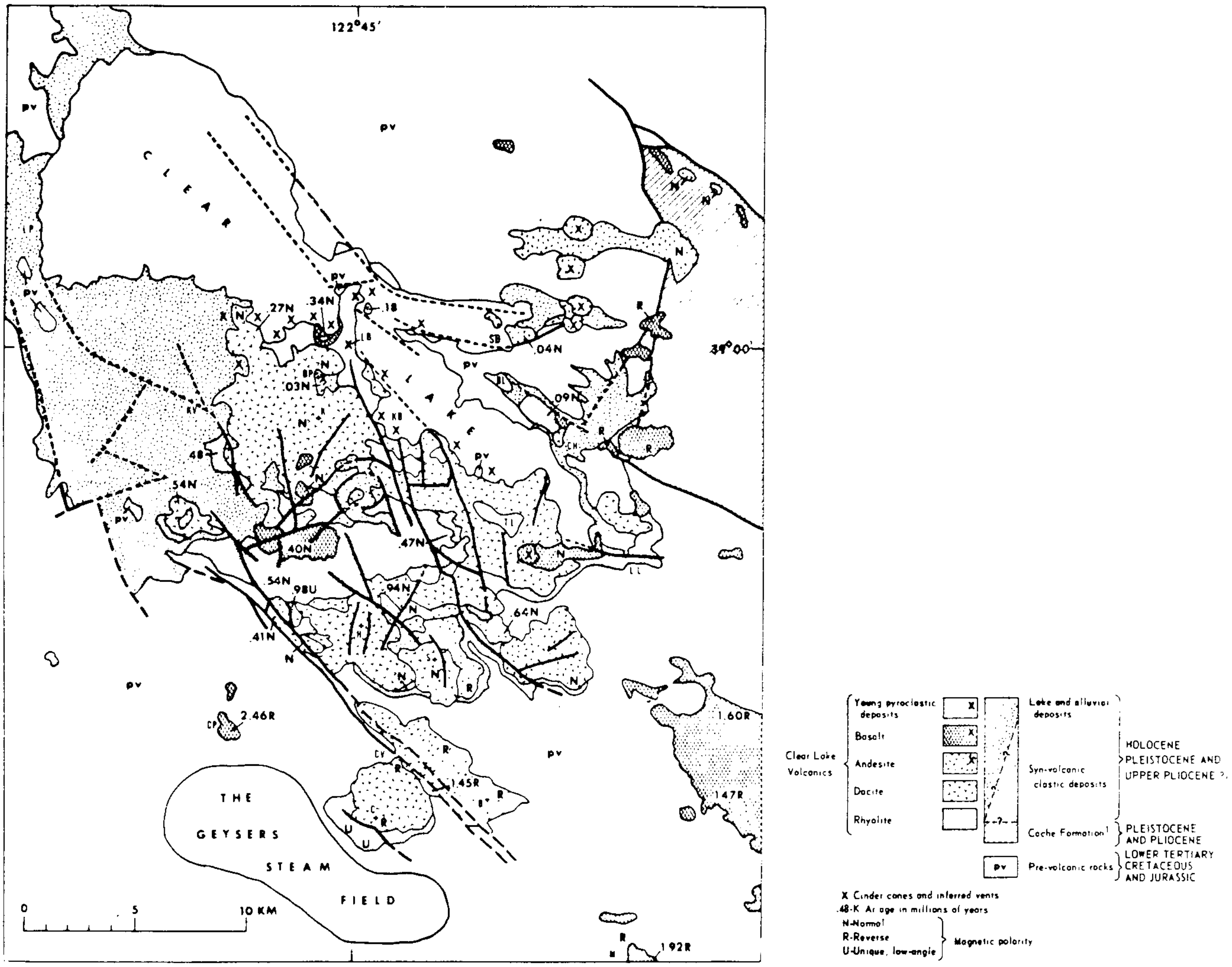

Fig. 5.
Generalized geologic map of Clear Lake volcanic field, showing K/Ar ages and magnetic polarities. Lake and alluvial deposits are shown only near Clear Lake. Order of volcanic units in explanation is not sequence of eruption. Lateral extent of cinder cones shown where associated with flows. Contacts 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 modifed 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 ≃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 psudo-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 ± phengite ± lawsonite ± albite ± jadeite ± glaucophane ± 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

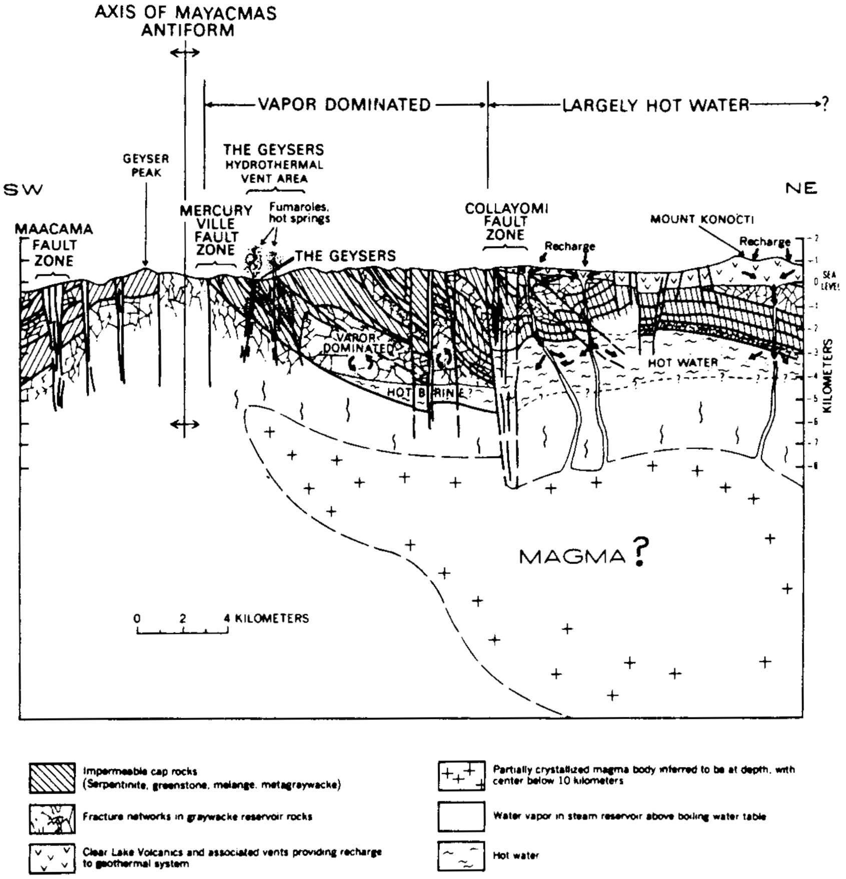

Fig. 6.
Structural model for The Geysers-Clear Lake geothermal regime. Cross-section through The Geysers-Clear Lake region, from the Maacama fault zone on the southwest, to Mount Konocti on the northeast, depicting structural elements of The Geysers-Clear Lake geothermal system; McLaughlin (1977).

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

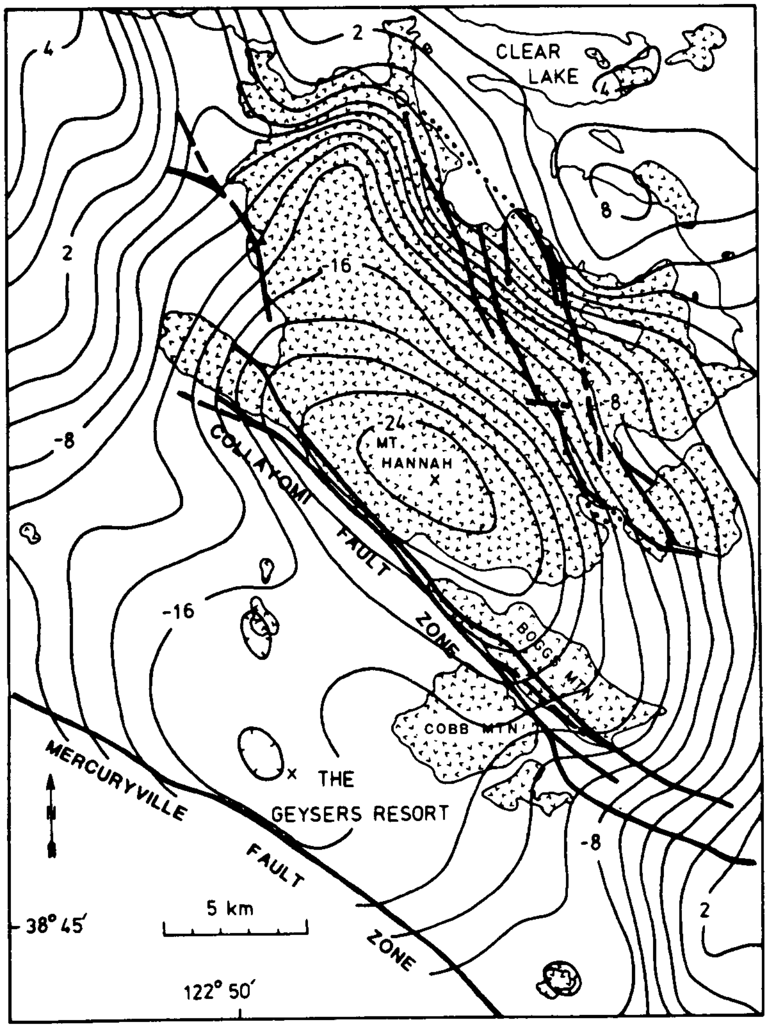

Fig. 7.
Residual Bouguer gravity of The Geysers-Clear Lake area, from Isherwood (1976), reduced at 2.67 gm/cm^3; 2 milligal contour interval. The Clear Lake Volcanics are shown with a V-pattern. The Collayomi fault zone divides the major gravity low into northeast and southwest lobes, and the Mercuryville 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

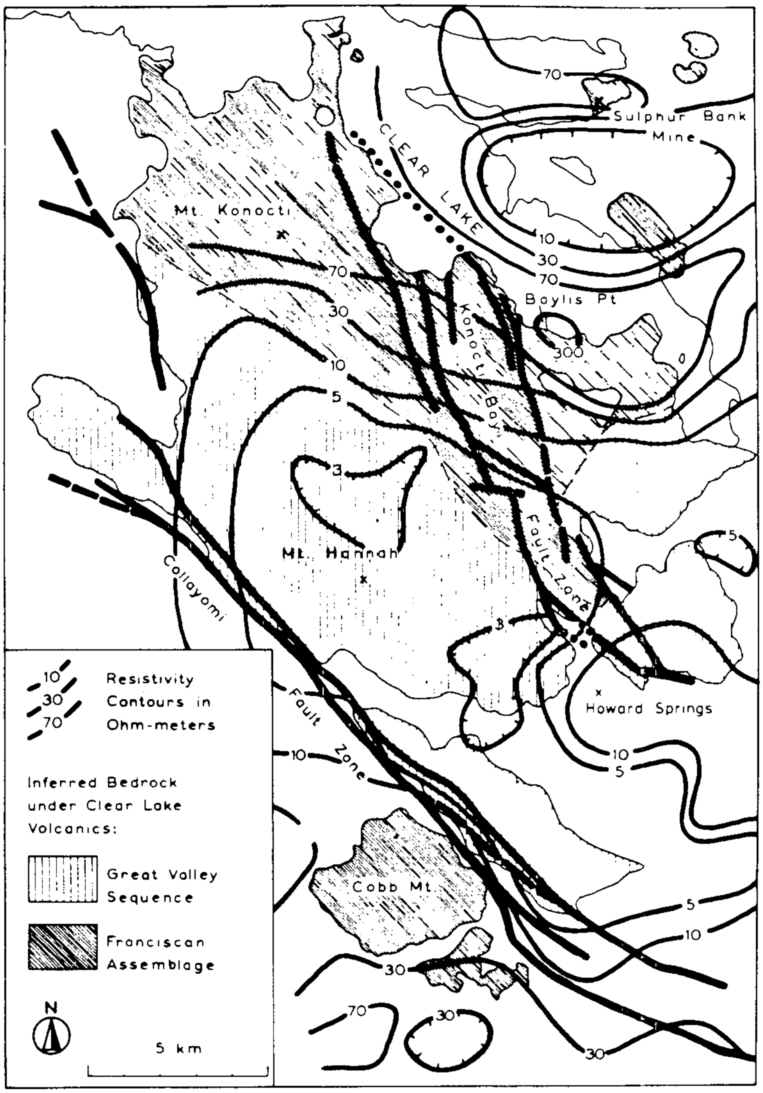

Fig. 8.
Outline of Clear Lake volcanic field with resistivity contours (Stanley and others, 1973) and two patterns indicating the two major types of bedrock under the volcanic field. Heavy lines are major fault traces; figure from Goff et al. (1977).

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 stongly 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,

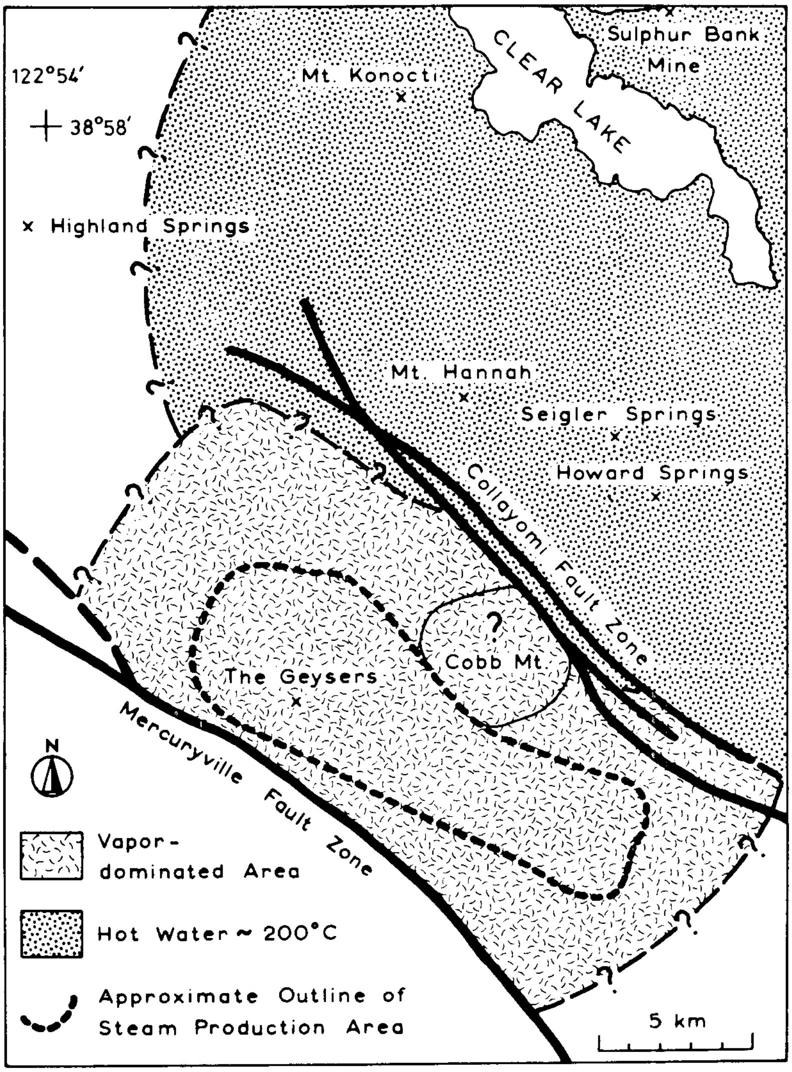

Fig. 9.
Approximate inferred limits of vapor-dominated and hot water-dominated areas; heavy lines are major fault traces; Goff et al. (1977).

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.