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THE CLEAR LAKE VOLCANICS:
TECTONIC SETTING AND MAGMA SOURCES

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ABSTRACT

The Clear Lake Volcanics may be the latest surface manifestation of a mantle hot spot that has left a track of Tertiary and Quaternary volcanic centers in the California Coast Ranges. These centers are progressively older to the south and are anomalously close to the former position of the subduction zone between the North American and Farallon crustal plates. Although initiation of volcanism may be correlated with cessation of subduction, problems of geometry and heat transfer probably preclude magma genesis from the newly detached slab of oceanic crust.

One or more predecessors of an inferred shallow magma chamber have been located beneath the central part of the field since about 0.6 m.y. ago, and perhaps since 1.1 m.y. ago. The current chamber is the ultimate source of heat for the vapor-dominated geothermal system at the Geysers and the inferred hot-water geothermal system beneath the volcanic field. Geophysical studies locate the magma chamber in Franciscan rocks and underlying crustal rocks of oceanic and possible continental affinity. Strontium isotopes, major and trace elements, and seismic velocities indicate that basaltic magmas have been generated from several mantle sources which probably consist of pyroxenite, peridotite, and eclogite. The many lavas, which as a group show a complete range of composition from basalt to rhyolite, are the products of fractional crystallization, wallrock assimilation, and magma mixing which have affected the primary melts from the mantle. The effect of assimilated Franciscan rocks is obscure, but incorporation of ophiolitic ultramafic rocks may show as elevated MgO content and variable Cr content. Rhyolite lavas of each age group show similar levels of incompatible trace elements, considerably less than the strong enrichments in major ash flows (Bishop Tuff, Bandelier Tuff). The lower abundances may result from regional differences of sources or may suggest that, as a result of the active tectonic setting, the Clear Lake magma system has leaked frequently enough to prevent the buildup of volatiles necessary for a voluminous ash-flow eruption. The most recent volcanic activity is northeast of the main volcanic field and has associated thermal fluids, possibly above a new focus of deep heating. In that area, expected future volcanic activity will probably be mafic in composition and will form pheumatophagic craters, cinder cones, or flows. However, the large magma chamber suggests that a catastrophic, silicic ash-flow eruption, with attendant caldera collapse, is also possible.

Numerous faults of northwest to north-northwest trend are related to right-lateral stress of the San Andreas system. The possibly active northwest-trending Collayomi and north-northwest-trending Konocti Bay fault zones break the Clear Lake Volcanics and show geomorphic evidence of late Pleistocene strike-slip, normal, and thrust movements. Part of the Collayomi fault zone showed ground breakage in the 1906 San Francisco earthquake. Fault directions and displacements are those expected by analogy with clay-cake modelling of right-lateral systems. Two north-south alignments of mafic vents, 0.35-0.5 m.y. and 0.01-0.2 m.y. old, fit the expected orientation of tension fractures, whereas vents for dacites from 0.35-0.5 m.y. and for basaltic lavas from 1.3-2.0 m.y. tend to be aligned northwest or north-northwest. At depth in Franciscan rocks, faults probably have produced fracture permeability which is important in the localization and accessibility of geothermal fluids.

INTRODUCTION

The Clear Lake volcanic field (figs. 13 and 14) and the late Pliocene and early Pleistocene Sutter Buttes (Williams and Curtis, 1977) are the only Quaternary volcanic fields that lie west of the southern projection of the Cascade trend of Quaternary volcanism. However, the Clear Lake volcanic field is the youngest and most northerly of several volcanic fields (Sonoma, Tolay, Berkeley Hills, Quen Sabe, Neenach-Pinnacles) that generally increase in age southward and have erupted in similar geologic settings: in the structurally complex terrane of Franciscan assemblage, Great Valley sequence, and ophiolites close to the San Andreas fault system. This geographic progression of age also holds within the Clear Lake volcanic field, where isotopic ages and the eruptive sequence show a general decrease in age northward from 2 m.y. in the south to about 10,000 years in the north (Donnelly-Nolan and others, this volume). Although any volcanic system young enough to produce surface thermal anomalies may be of geothermal significance, silicic systems tend to develop high-level magma chambers and show the greatest geothermal potential at economically accessible depths (Smith and Shaw, 1975).

A shallow magma chamber, defined by geophysical evidence, underlies the Clear Lake volcanic field. Heat from that chamber, its wallrocks, and conjectural newly developing magma systems is producing the geothermal resources of the Geysers-Clear Lake area. In this paper we examine data on the structural setting of the Clear Lake volcanic field, its volcanic rocks, depth of generation of magma, location of magma chambers, and the possible processes that have modified deep-source magmas to produce the erupted lavas.

Many geoscientists have added to our comprehension
of the problems of Clear Lake geology and volcanology by stimulating discussions in the field. We are grateful to residents of the area for access to their properties and succor during the long hot summers. Republic Geothermal Inc., Aminoil USA, Magma Energy Inc., Dow Chemical Co., Getty Oil Co., Pacific Energy Corp., Union Oil Co., Shell Oil Co., E.B. Towne, Geothermal Resources International Corp., and E.V. Ciancanelli provided geologic information or subsurface samples to further the geothermal knowledge of the Geysers-Clear Lake area.

STRUCTURE

The Clear Lake Volcanics provides structural markers that record the stress field during the past 2 million years in the Geysers-Clear Lake area. Faults, particularly those of northwest and north-northwest trend, provide major avenues for movement of thermal fluids to the surface (Goff and others, 1976, 1977). Many of the numerous faults have produced fracture porosity at depth, which is important for geothermal production in the Geysers steam field (McLaughlin, 1975, 1977a) and which will be important in exploration and development to the north in the inferred hot-water field (Goff and others, 1976, 1977; Goff and Donnelly, 1977; Donnelly, Goff, Thompson, and Hearn, 1976). Repeated faulting during the development of one or more magma chambers may explain the abundance of separate vents and flows within the Clear Lake volcanic field.

The volcanic field lies within the San Andreas fault system although the main fault zone is 60 km to the west. The San Andreas system is increasingly recognized as affecting a wide zone beyond the main fault by accumulation of strain or creep on numerous subsidiary fault zones (Thatcher, 1975, 1977). The two main fault zones in the Clear Lake volcanic field (figs. 14 and 15) are the Collayomi fault zone of northwest trend (Donnelly, McLaughlin, Goff, and Hearn, 1976) and the Koniocai fault zone of north-northwest trend (Goff and others, 1976).

Both fault zones are part of the San Andreas system and when more detailed mapping is available to the southeast, both zones may extend as far as or into the

![Diagram](image.png)

**Figure 13.** Ages of volcanic rocks, central Coast Ranges, California, from Allen (1946), Donnelly-Nolan, Hearn, Curtis, and Drake (this volume), Evernden, Savage, Curtis, and James (1964), Morse and Bailey (1935), Prowell (1974), Mankinen (1972), Radbruch and Case (1967), Turner (1970) and Turner, Curtis, Berry, and Jack (1970). Ages are by potassium-argon and by correlation with formations dated by faunal assemblages.
active Green Valley fault zone (Frizzell and Brown, 1976). Both show evidence of late Pleistocene movement: valleys, ridges, and other geomorphic features and Pleistocene volcanic rocks are offset. As further evidence of Pleistocene movement, serpentinite is squeezed up between volcanic units as young as 1.1 m.y. (Hearn and others, 1975b; Donnelly, McLaughlin, Goff, and Hearn, 1976; Donnelly, Hearn, and Goff, 1977). Felt earthquakes reported by residents near each zone and earthquake epicenters close to the Konocti Bay fault zone (Bufo and others, 1976; this volume) suggest that the zones are active. Southeast of Kelseyville, ground breakage for a distance of about 1.6 km in the 1906 San Francisco earthquake (Lawson, 1908, p. 188) corresponds in location and approximate direction with the southeastern part of the Big Valley fault (Lake County Flood Control and Water Conservation District, 1967), which is an offshoot of the Collayomi fault zone. Thus the southeastern part of the Big Valley fault is active. Within both the Collayomi and Konocti Bay zones, most faults show normal displacement. Along one fault in the Collayomi zone, right-lateral offset of volcanic rocks 0.5–0.6 m.y. old indicates an average movement of about 1 mm/yr over the past 0.5 m.y. Thrust or reverse faults in the Collayomi zone near Glenbrook in NE Sec. 25, T. 12 N., R. 8 W. (Donnelly and others, 1977, p. 37) and in the Konocti Bay zone along Soda Bay Road on the east edge of Ely Flat in the SW. cor. sec. 27, T. 13 N., R. 8 W. (Hearn and others, 1975b, 1976a) are shallow subsidiary structures which are consistent with and to be expected in a strike-slip fault system. Changes in horizontal distance across the Clear Lake volcanic field and to the southwest are consistent with active right-lateral deformation (Lofgren, this volume).

Faults of northwest and north-northwest trend are dominant within the Clear Lake volcanic field, and many of these faults are part of the Collayomi or Konocti Bay fault zones. These directions are also typical in fault zones to the southwest (McLaughlin, 1975, 1978) and northeast of the Clear Lake volcanic field. Faults of northeast trend are rather common, but those of east-west trend are less abundant. The overall pattern of faulting (fig. 15) fits a system of deformation related to a right-lateral northwest-southeast strike-slip couple by analogy to deformation of clay-cake models (Cloos, 1955; Wilcox and others, 1973). Expected directions of synthetic and antithetic shear faults would be at about 15° (north-northwest) and about 80° (northeast) respectively from the main couple, and maximum potential for tension fracture opening would be at about 45° (north-south) from the main couple. In the Clear Lake field, north-northwest-trending faults should show right-lateral strike-slip, and some do show it. By analogy to models, northeast-trending faults should show left-lateral strike-slip, but their lateral displacements could be small because of rotation effects (Wilcox and others, 1973). Some northeast-trending faults do locally show offsets which could be in part left-lateral strike-slip, but the apparent major displacement is normal slip.

The direction of maximum tension significantly corresponds to two north-south-trending zones of upward penetration and eruption of mafic magma: the zone of vents of 0.55 m.y. and younger basaltic andesite that extends across Mount Konocti, and the zone of young mafic cinder cones that extends from Roundtop Mountain on the south to Round Mountain in High Valley on the north. Some basaltic lavas that erupted in these two zones have "primitive" compositions characteristic of deep-source magma that has had minimal interaction with wallrocks or other melts on the way up. The ascent of deep-source magma may have been facilitated by tension fractures. Similarly, tension may have helped to create the space for shallow magma chambers. Other directions of vent alignments are northwest for the 0.55–0.35 m.y. dacites, and northwest to north-northwest for the early basalts; both are parallel to dominant regional fault directions that could have provided access for magma to the surface.

Also, by analogy with clay-cake models, faults along a major fault zone that follows a discontinuity at depth would be expected to be initially arranged in echelon, each segment trending 15° from the zone, and to later form an anastomosing group of active and inactive faults as new faults continue to develop (Rogers, 1973; Wilcox and others, 1973). With continued deformation, the antithetic northeast faults would be rotated clockwise, eventually far enough that new faults would form at about 80° from the main couple. In the Clear Lake Volcanics, deformation has probably been insufficient for detectable rotations except for small blocks within fault zones. Rotations should be more apparent in older units, but they have not been detected in paleomagnetic directions (Mankinen and others, 1976, this volume).

The Clear Lake topographic basin is delineated in part by faults of north, north-northwest, and west trend (Sims and Rymer, 1974, 1976). Formation of the Clear Lake basin and the earlier, geographically separate basin of deposition of the Cache Formation to the east (Anderson, 1936; Hodges, 1966; Rymer, 1978; 1981) could be related to subsidence between strike-slip faults by the mechanism outlined by Crowell (1974). The likely causative strike-slip faults would lie on the northeast side of Clear Lake and farther northeast within the Wilson Valley fault zone, but strike-
slip displacement has not been proved. Although the outline and depth of the lake have changed in the past 50,000 years, the lake basin has been collecting sediment for at least the past 0.6 m.y. as sedimentation kept pace with subsidence (Sims, 1976; Donnelly, 1977). South of Kelseyville, northward tilting of lake and fluvial deposits (Kelseyville Formation, Rymer, 1978; 1981; equivalent to basin deposits of Kelseyville, Hearn and others, 1975b, 1976a), and the presence of deeper water and steeper slopes along the northeastern shores of Clear Lake suggest that northward or north-eastward tilting of the lake basin has continued to recent time.

The overall structural pattern of the San Andreas fault system is overprinted by more local features related to volcanism. The large circular basin southeast of Mount Konocti, 1.6 km in diameter, may be related to collapse after eruptions of biotite rhyolite or dacite. The arc-like outcrop band of the rhyolite of Thurston Creek suggests a possible ring-fracture distribution of vents 0.6 m.y. ago. The abundance of related rhyolitic pumice in the basal part of the Kelseyville Formation (Rymer, 1981) suggests that eruption of the rhyolite could have produced or closed the basin, but evidence of large-scale caldera collapse is lacking. There is no known northern, eastern, or western counterpart to the arc, nor are there any age-equivalent volcanic units along the projection of the arc in those directions. The semicircular shape of the northern shore of Clear Lake suggests partial control by circular collapse, but the pattern could be a fortuitous result of deltaic sedimentation and linear north- to northwest-trending fault segments along the borders of the topographic basin.

No young volcanic rocks are known to be exposed around the northern part of the lake, and the northern extent of the Clear Lake Volcanics beneath the lake bottom sediments has not been determined.

The active tectonics of this region will be documented by the monitoring of changes in elevations, horizontal distances, and lake level (Lofgren, 1973; this volume). Recently established close-spaced stations have potential for determining the displacement rate on individual faults.

**OCCURRENCE AND LITHOLOGY OF THE CLEAR LAKE VOLCANICS**

Eruptive rocks of the Clear Lake Volcanics range in composition from basalt to rhyolite and occur in four age groups: 0.01–0.1 m.y., 0.30–0.65 m.y., 0.8–1.1 m.y. and 1.3–2.1 m.y. (fig. 16) (Donnelly-Nolan and others, this volume). Basalt, basaltic andesite, and andesite occurs primarily as rubbly to massive domes and thick flows, in accord with its higher viscosity. Rhyolite occurs as domes, as large flows, and as fragmental pumiceous deposits of tuff to agglomerate, which have been deposited by air-fall, or less commonly by mudflow. In contrast to the abundant dacitic ash flows of the Sonoma Volcanics, ash flows are absent in the Clear Lake Volcanics.

The rock names used in this paper are based mainly on chemical composition, but those for unanalyzed volcanic units are based on hand-lens mineralogy, petrography, and flow characteristics. In general, basalt contains less than 54 percent SiO₂, basaltic andesite 54–58 percent SiO₂, andesite 58–62 percent SiO₂, dacite 62–71 percent SiO₂, and rhyolite greater than 71 percent SiO₂; considered on a water-free basis, the respec-
Petrographic data are given by Anderson (1936) and Brice (1953). All the basalts and most of the basaltic andesites contain olivine phenocrysts (1–10 percent); plagioclase phenocrysts, generally less than 2 mm in size, are present in a few flows and tephra deposits of basalt and basaltic andesite. The groundmass in these rocks consists of clinopyroxene, olivine, and plagioclase.

Andesites typically contain phenocrysts of plagioclase, orthopyroxene, and clinopyroxene, and rarely in the Clear Lake field.
olivine, hornblende, or obvious ilmenite. Amounts of pyroxene and plagioclase phenocrysts vary widely from one andesite unit to another.

The many varieties of dacite range from strongly porphyritic to weakly porphyritic, and all contain phenocrysts of plagioclase, clinopyroxene, orthopyroxene, and quartz. Most varieties contain small amounts of biotite, and many varieties contain both biotite and hornblende. Only a few contain olivine. Strongly porphyritic dacites contain sanidine phenocrysts and are mainly of more silicic, rhydacitic composition. Most, but not all, of the weakly porphyritic dacites are less silicic. Strongly porphyritic dacites contain a range of sizes of feldspar phenocrysts (as much as 3 cm in some) and contain several compositions of feldspar and pyroxene phenocrysts in the same rock (Anderson, 1936; Brice, 1953; Donnelly, 1977). Such variations in phenocryst compositions have been cited as evidence of a hybrid origin (Anderson, 1936; Brice, 1953; Eichelberger, 1975). A few weakly porphyritic dacites have widespread glassy chilled facies on the top, base, and edges of flows.

Rhyolites are of two types, biotite-bearing and nearly biotite-free. Biotite rhyolites are commonly perlitic in glassy facies and typically crystal-rich (15–30 percent total of quartz, plagioclase, and sanidine phenocrysts; 0.5–5 percent biotite phenocrysts). Biotite rhyolites have quartz and feldspar phenocrysts of uniform size (2–5 mm) and lack the large size and multiple compositions of feldspar seen in the strongly porphyritic dacites. Rhyolites lacking biotite or containing less than 0.5 percent biotite are typically crystal-poor (less than 3 percent phenocrysts) and have widespread obsidian facies. Of the biotite-poor rhyolites, only the rhyolite of Bonanza Springs formed widespread pyroclastic deposits. Several of the biotite rhyolites occur mainly as pumiceous pyroclastic deposits although none are as extensive as the rhyolite of Bonanza Springs.

Two types of lithic inclusions and large quartz grains of problematical origin occur in the Clear Lake Volcanics. Type 1 inclusions have diabasic to granular texture and have larger grains and more mafic composition than their host; they are common in some dacites and most biotite rhyolites. Type 2 inclusions are schistose to granular metamorphic rocks; they are common in the andesite of Perini Hill, are less common in the andesites of Seigler Canyon, Boggs Mountain, and Grouse Springs, and are quite rare in basaltic andesites and basalts. Clear, irregular to rounded quartz grains, commonly 1–10 mm in size and rarely as large as 5 cm, occur in more than half the basaltic andesites, are abundant in the andesite of Perini Hill, and are less abundant in the andesites of Seigler Canyon, Split Top Ridge, Boggs Mountain, and Grouse Springs.

Type 1 inclusions (I on fig. 17) have a relatively narrow position within the basaltic to andesitic range of compositions and are probably cognate with the Clear Lake Volcanics because they are not found as exposed country rocks. Type 1 inclusions are possibly (1) derivatives of their host flow that crystallized at hypabyssal depths, (2) recrystallized inclusions of earlier volcanic rocks, or (3) blobs of more mafic magma which were partly chilled upon injection into the more silic, cooler part of a magma chamber as proposed by Eichelberger and others (1976).

Type 2 inclusions are silicic to aluminous in composition and commonly contain garnet, cordierite, and spinel. Such inclusions could have been derived from (1) Franciscan or Great Valley shaly or silty rocks, or (2) rocks beneath the Franciscan assemblage. The schistose metamorphic fabric suggests regional rather than contact metamorphism and may indicate that a sialic basement of regional metamorphic rocks lies beneath part of the Clear Lake volcanic field. Such a sialic basement would be anomalous in or beneath the Franciscan, which is commonly assumed to be underlain by oceanic crust (Eaton, 1966; Warren, 1968; Bailey and others, 1970), although seismic data do not preclude the presence of continental crust.

Brice (1953) linked the origin of quartz grains in the andesite of Perini Hill and in some flows of basaltic andesite to disintegration of quartz-rich type 2 inclusions, a conclusion with which we concur for andesite of Perini Hill. Other proposed origins for quartz inclusions in basaltic and andesitic rocks are (1) rapid transport and chilling of a basaltic melt in which quartz phenocrysts are stable at 25 kilobars or higher pressures (Nicholls and others, 1971), (2) recrystallization of chert inclusions, or (3) phenocrysts surviving from silicic magma which mixed with basalt.

PRESENT AND PAST MAGMA CHAMBERS

The presence of a magma chamber (fig. 13) beneath the Clear Lake volcanic field is indicated by geophysical evidence. Gravity surveys (Chapman, 1966; Isherwood and Chapman, 1975) show a circular 25-mGal gravity low about 20 km in diameter, centered over Mount Hannah in the south-central part of the volcanic field (Isherwood, this volume). The gravity anomaly and aeromagnetic data (U.S. Geological Survey, 1973) have been interpreted as expressions of a spherical to cylindrical magma chamber about 14 km in diameter whose top is within 7 km of the surface (Chapman, 1966, 1975; Isherwood, this volume). In addition, teleseismic P-waves arriving within the area of the gravity low show delays of 0.5–1.5 seconds that are consistent with the presence of a subsurface mass containing a large proportion of melt and having a hori-
zontal extent roughly equivalent to the size of the source of the gravity anomaly and a vertical extent to 30 km depth (Iyer and others, this volume). Seismic hypocenters are no deeper than 6 km in the area of the gravity low (Bufe and others, 1976; this volume). Electrical resistivity surveys may be sensing some shallow indirect effects (hot fluids, high salinity) of a magma chamber (Stanley and others, 1973). Although resistivity could be sensing the presence of magma at depths greater than 5 km (Stanley and others, 1973), such data are ambiguous and could be explained by other models without magma at 5–7 km depth (Isherwood,

![Diagram](image)

**Figure 16.** Present distribution of young volcanic rocks in Clear Lake area. A, Sonoma Volcanics (patterned) (2.9 m.y. and older) and age group 4 (1.3–2.1 m.y.). B, Age group 3 (0.8–1.1 m.y.). C, Age group 2 (0.30–0.65 m.y.). D, Age group 1 (0.01–0.1 m.y.). Vents shown only for Clear Lake Volcanics. Compiled from Hearn, Donnelly, and Goff (1976a), McLaughlin (1978), Fox, Sims, Bartow, and Helley (1973), Koenig (1963), and California Department of Water Resources (1962).
The presence of one or more magma chambers is suggested by the large volume of silicic relative to mafic volcanic rocks (Smith and Shaw, 1975).

Smith and Shaw (1975) estimated a considerably larger magma chamber for the Clear Lake system on the basis of the distribution of vents, regardless of composition, and of the diameter of the -35-mGal gravity contour of Chapman (1966). The vertical extent of the magma chamber could be greater than that inferred by Isherwood (1975) and Chapman (1975) if there is a substantial body of higher density mafic magma beneath the silicic magma. The mafic part could show little or no expression in the gravity data or, if denser than its surroundings, could cancel out part of the gravity low that is due to overlying silicic melt and hot rock. A deeper, more mafic root of the magma chamber is likely, and its detection may depend on seismic surveys to delineate the region of shear-wave attenuation or P-wave delays. The lack of volcanic rocks younger than 1 m.y. in the Geysers steam field conflicts with an inferred shallow lateral extension of the magma chamber (Isherwood, 1975; McLaughlin, 1977a) based on gravity data.

The inferred magma chamber may have an overlying shadow zone (Smith and Shaw, 1975), an area of dacite and rhyolite in which no mafic vents occur, presumably because ascending dense mafic magma could not penetrate the lower density silicic magma in the upper part of the shallow magma chamber. However, the evidence is ambiguous as none of the most recent volcanic rocks occur above the inferred magma chamber. In the most recent eruptive period, 0.1 m.y. to 10,000 years ago, igneous activity shifted from the geophysically inferred magma chamber to the area near the southeastern arms of Clear Lake and northeast of the lake (fig. 16D). Most of the lavas and tephra were basalt, basaltic andesite, or andesite, rocks that suggest a new cycle of deep-source magma generation, heating of the crust, and possible development of other magma chambers. Judging from the fractionated composition and the large negative europium anomaly of the rhyolite of Borax Lake, at 0.09 m.y., it is the only eruptive unit in the youngest age group that may have evolved in a magma chamber. Whether the Borax Lake flow was fed laterally from the inferred main magma chamber or derived from its own subjacent chamber is unknown. Existing geophysical data are insufficient to determine whether one or more small magma chambers are present near Borax Lake or farther northeast of Clear Lake.

Evidence of a major magma chamber for age group 4 rocks (1.3–2.1 m.y.) (fig. 16A) is nonexistent. Basalts and basaltic andesites erupted from widely dispersed
THE GEYSERS-CLEAR LAKE GEOTHERMAL AREA, CALIFORNIA

The diagrams show the distribution of various elements in weight percent as a function of silica content. Each graph represents a different element, with points indicating the concentration values. The x-axis represents the silica content in weight percent, while the y-axis shows the corresponding element content in weight percent.
Figure 17.—Variation of major elements with silica for Clear Lake Volcanics, three samples of rhyolite from the Sonoma Volcanics, and samples of wallrocks. Analyses have CO₂ and equivalent CaO removed as calcite and are normalized to 100 percent dry weight, except for average Franciscan graywacke and additional point (% symbol) for Great Valley sandstone plotted with CO₂ removed as CO₂. Sources of data: Anderson (1936), Carmichael (1967), and unpublished analyses by U.S. Geological Survey, mainly by rapid rock analysis methods.
vents but were concentrated in a northwest-trending zone of deep magma access possibly controlled by the regional right-lateral stress system. Andesitic eruptive activity was focused in the Boggs Mountain area. The 1 km$^2$ of andesitic to rhyolitic volcanic rocks at Pine Mountain are probably cogenetic and could have been derived from a small magma chamber, which would be totally cooled by now but may contribute to a local gravity low (Isherwood, 1976, fig. 4).

A logical model of magma chamber evolution is that the current inferred chamber has evolved from one or more predecessors. Such early chambers may date back at least to the eruption of the 5-km$^2$ rhyolite of Alder Creek about 1.12 m.y. ago, during group 3 volcanism (1.1–0.8 m.y.), and may have been initiated by deep injection of basaltic magma 1.3–1.6 m.y. ago. The 1.02-m.y. rhyolite of Bonanza Springs and most of the andesites and dacites of group 3 age were vented in an elongate east-west 7-by-14-km area, the west part of which is directly above the current magma chamber.

This series of eruptions culminated in the Mount Han-nah edifice of several dacite bodies erupted within less than 5,000 years, possibly within 100 years (Mankinen and others, this volume; Donnelly-Nolan and others, this volume). The rhyolite of Alder Creek (1.12 m.y.) erupted earlier at Cobb Mountain either from the same chamber or from a satellitic chamber to the south. Down-faulting of part of that rhyolite has been inter-preted as the result of possible collapse above a local magma chamber (Goff and McLaughlin, 1976).

Nearly all silicic eruptions of group 2 (0.30–0.65 m.y.) age occurred to the north of the group 3 eruptions (fig. 16B, 16C). Several dacite flows and a rhyolite flow of about 0.6 m.y. age indicate that a magma chamber or chambers were in existence by that time. Locations of group 2 silicic vents do not support a simple pattern of arcuate distribution above a single magma chamber. The 4-km$^2$ rhyolite of Thurston Creek, an early group 2 flow, erupted from vents along a 13-km northward-concave arc and may have initiated formation of part of the Clear Lake basin. If the arc is an expression of a ring-fracture zone, it has no northern counterpart and has no simple relation to the dacite vents of similar age or to the current inferred magma chamber.

Dacites of 0.5–0.6 m.y. age, slightly older or younger than the rhyolite of Thurston Creek, erupted from widely distributed vents as much as 19 km apart (at the west end of the rhyolite arc, and 1–5 km north, 8 km east, and 5 km south of the arc). Their pattern suggests that (1) the magma chamber was much larger than the present one, or (2) several magma reservoirs existed, or (3) magma migrated significantly in a lateral direction.

Dacites of 0.5–0.35 m.y. age vented in a west-northwest-trending zone 5 by 20 km which lies mainly to the north of the 0.5–0.6 m.y. pattern. These eruptions culminated at the northwest end of the zone in the voluminous edifice of Mount Konoci. This elongate zone of dacite vents suggests that shallow ascent of magma was controlled by regional northwest-trending structures rather than by arcuate structures generated by a subjacent magma chamber.

The apparent shadow zone for group 2 rocks permits the correlation of a 0.65–0.35-m.y. magma chamber and the present chamber (figs. 14, 16C), but the shadow zone is not well defined. The group 2 chamber is limited on the west by the 7-km-long, north-trending zone of basaltic andesite vents which runs from the basaltic andesite of McIntire Creek (about 0.55 m.y.) to the mafic vents (about 0.35 m.y.) high on Mount Konoci. To the east the chamber is limited only by a concealed basaltic vent (Donnelly, 1977) inferred to have been in the vicinity of the southeastern arm of Clear Lake and to have contributed mafic tuff to the Lower Lake For-mation (Rymer, 1978, 1981; equivalent to basin deposits of Wildcat Canyon, Hearn and others, 1976a). The chamber is not limited to the north or south by any known group 2 mafic rocks. The western limit suggests that the dacites in the Kelsey Creek-Mount Olive area were erupted from a separate magma chamber, or that if they were fed laterally from the main chamber, the connecting conduit had crystallized by about 0.55 m.y. ago.

Mount Konoci contains the largest volume of dacite in the volcanic field (Donnelly-Nolan and others, this volume) and must have been fed from a sizable magma chamber, but the interleaved mafic units show that Mount Konoci was beyond the northern limit of the chamber at that time and was probably fed laterally from the main chamber. Where such extensive lateral migration of magma has occurred, the limits of a shadow zone are indistinct. Mount Konoci is beyond the northern limit of the present chamber.

Calculations for conductive cooling indicate that a spherical magma chamber 14 km in diameter (1,430 km$^3$) would have cooled to less than 650°C and completely crystalized in about 0.5 m.y. (Smith and Shaw, 1975). The calculations imply that if the current magma chamber has been present for the past 0.6 m.y. it was originally much larger, or that it has been resupplied with magma and heat several times. Either seems more likely than the alternative that several magma chambers have developed and cooled in nearly the same space.

In the regional strike-slip tectonic regime of the Clear Lake area, a simple arcuate distribution of silicic
vents and a central shadow zone, more typical of stable areas, may not develop, because the deep and shallow ascent of magma may be dominated by regional structures and frequent fracturing. However, a shallow magma chamber and its hot aureole would be expected to transmit the regional strike-slip stresses poorly or not at all, and could cause a tectonic "shadow zone" of fewer faults above the magma chamber. In the Clear Lake volcanic field, a tectonic shadow zone is doubtful. Although faults may be somewhat less numerous above the northeastern half of the geophysically inferred magma chamber (figs. 14 and 15) than farther northeast, the Collayomi fault zone crosses the vertically projected position of the magma chamber. More significant is the lack of any seismic events at depths greater than 6 km in the area of the inferred magma chamber (Bu"fe and others, this volume).

Although regional stresses and local uplift can contribute to creation of the space occupied by magma at depth, some of that space is probably developed by stopping, partial melting and assimilation of wallrocks; these processes could have significant effects on the temperature and chemical variation of the magma. For the inferred position of the present magma chamber, extending from about 7 to 21 km depth (Isherwood, 1976; this volume), or to 30 km depth (Iyer and others, this volume), such wallrocks would be of the Franciscan assemblage to a depth of 13 to 15 km, and at greater depth would be the 6.8 to 7.2 km/s crust beneath the Franciscan. These assumed wallrock depths are based on seismic profiles to the west (Warren, this volume) and in the San Francisco Bay area (Warren, 1968) and on experimental determination of seismic velocities of Franciscan clastic and metaclastic rocks (Stewart and Peselnick, 1977). If lower crustal rocks are a major influence on the Clear Lake magmas, then the predominance of silicic lava compositions could indicate that part of the lower crust is sialic and of continental origin, because predominance of silicic lavas is atypical of areas underlain by oceanic crust.

In summary, a magma chamber in the Franciscan and underlying crust is indicated by geophysical data. Geologic data suggest that a magma chamber has been present in that location since about 0.6 m.y. ago. An earlier chamber (0.8 to 1.1 m.y.) may have evolved into the present chamber, but it could have been centered farther south.

CHEMISTRY

Major-element compositions for the entire age span of the Clear Lake Volcanics vary continuously from basalt to rhyolite with no gap in the dacite range (fig. 17). However, within each of the four age groups the range is not complete. Group 4, the oldest, lacks rocks with 61 to 67 percent SiO2. Group 3 contains no basalt or basaltic andesite. In group 2, the range 60 to 63 percent SiO2 is represented only by type 1 diabasic-textured inclusions. Group 1 lacks dacite other than the hybrid members of the basalt-dacite-rhyolite series at Borax Lake (Anderson, 1936; Bowman and others, 1973). In basalts and basaltic andesites, the considerable scatter in SiO2, TiO2, and other oxides may be indicative of generation from several deep sources. The basalts and basaltic andesites as groups are not obviously related by olivine fractionation from a single parental basalt. On SiO2 variation diagrams (fig. 17) for all the Clear Lake Volcanics, K2O, CaO, and total FeO show a linear variation with SiO2, with little scatter, whereas Al2O3 and MgO show more scatter. Na2O shows a linear trend that changes by only about 1.5 percent across the entire SiO2 range.

Analyses are plotted (fig. 17) for three rock types which could have been assimilated: a sandstone (raho
titic SiO2 content) from the Great Valley sequence (Upper Cretaceous, unit IVd of Sve and Dickinson, 1970); an average Franciscan graywacke (rhyolitic SiO2 content, Stewart and Peselnick, 1977, table 2), and a type 2 inclusion, quartz-biotite-garnet-pyroxene schist (dacitic SiO2 content), from the andesite of Perini Hill. All three types plot within several oxide trends for the Clear Lake Volcanics on SiO2 variation diagrams. However, compared to volcanic rocks of equivalent SiO2 content, the schist is significantly higher in total FeO, the sandstone is significantly higher in CaO (in part due to carbonate cement, CO2 4.8 percent) and MnO, and both are lower in Na2O. The graywacke is higher in total FeO and in Na2O and is lower in K2O. Thus none of the three rocks can be an end-member for simple one-stage assimilation to account for the compositional variation of the Clear Lake Volcanics. Analytical data for various Franciscan rock types are needed to test assimilation models.

On an alkali-iron-magnesia (AFM) diagram (fig. 18), samples from the Clear Lake Volcanics show a diffuse trend across the central part of the diagram like that of lavas from the Cascade Range, but they tend to be lower in FeO and higher in MgO than average Cascade lavas (Anderson, 1936; Carmichael, 1964), possibly owing to interaction with ultramafic rocks and serpen
tinite at shallow depth. The AFM trend converges to
toward rhyolite from the widely scattered basalts and basaltic andesites, which have a wide range of FeO/ MgO ratios. The scatter of basalts and basaltic andesites indicates the likelihood of several parental mafic magmas. Although a few contemporaneous basalts or
basaltic andesites appear to be related by iron enrichment, there is no single fractionation trend among the mafic rocks.

Trace elements in the Clear Lake Volcanics show rather systematic variation relative to SiO₂, total Fe, differentiation index, and other measures of major-element variation, similar to relations in other basalt-andesite-dacite-rhyolite magma systems. Bowman, Asaro, and Perlman (1973) have shown closely linear trace-element variations in the dacite-rhyolite series near Borax Lake that indicate some mixing process of basalt and rhyolite. The basalt end-member of the series apparently was not found by Bowman, Asaro, and Perlman (1973), but the basalt of Arrowhead Road (Hearn and others, 1976a), adjacent to the rhyolite and dacite, is that end-member according to our analytical data for major and trace elements.

In each period of volcanism, five minor elements (Rb, Cs, Ta, Hf, and Th) and total rare-earth elements tend to increase with increasing SiO₂ and K₂O and reach about the same maximum values in rhyolites of each period. The maximum values are considerably below the extreme enrichment shown by some large ash-flow sheets such as the Bandelier Tuff (Smith and Bailey, 1966) and Bishop Tuff (Hildreth, 1977) in continental settings. The lower values for Clear Lake rhyolites may be in part a result of regional differences between continental and continental-border settings. The uniform values suggest that when the Clear Lake magmatic system lost its silicic fraction to the surface, these elements had reached a particular amount of enrichment in the upper part of the magma chamber. Approximately the same values are found for two bodies of rhyolite in the Sonoma Volcanics (Napa Glass Mountain, and an erosional remnant of welded ash-flow tuff northwest of Mount St. Helena).

Trace elements of basaltic affinity (Cr, Co, Zn, and Sc) show systematic decreases from basic to silicic rocks in the series and have more scattered values in the basalts and more uniform low values in the rhyolites. Of these elements, Cr varies in concentration in rocks of similar SiO₂ content through the whole series. Cobalt values, typically 1/4 to 1/20 of chromium, in part follow the high variability of Cr, but in a few rocks Co is nearly equal to Cr. Variability of these elements may indicate the addition of Cr and Co from the ultramafic rocks and serpentinite beneath parts of the Clear Lake Volcanics. Alternatively, some of their variability in intermediate rocks could reflect the Cr and Co content of parental basaltic melts, particularly if magma mixing has occurred. Cr and Co values range from 25 to 1,050 ppm and 24 to 56 ppm respectively in the basalts, suggesting (1) variability in deep sources of the basalts, (2) interaction with more shallow ultramafic rocks, or (3) varying amounts of preeruption separation of chrome spinel.

The total concentration of REE's (rare-earth elements) varies from a minimum of about 35 ppm in the most primitive basalt (of Caldwell Pines) to a range of about 110–180 ppm in rhyolites. Anomalously high total REE's are found in several units of the Clear Lake Volcanics peripheral to the main volcanic field: basal-

**Figure 18.** — AFM diagrams for Clear Lake Volcanics and other rocks. A = Na₂O + K₂O, M = MgO, F = total Fe as FeO + MnO + TiO₂. Lines join samples from units close in space and time. Outlined areas enclose samples from specific geographic areas. Lines from inclusion symbols point toward host rock. Dashed line shows trend of average composition of rhyolite, dacite, andesite, basaltic andesite, and basalt in the Cascade Range (Carmichael, 1964, table 8).
tic andesite of Table Mountain (338 ppm), and two of the northernmost early basalts (98 and 109 ppm).

Within the main volcanic field, anomalously high REE contents occur in several units that do not otherwise show evidence of strong fractionation. For instance, the basaltic andesite of Buckingham Peak contains high REE's (70–80 ppm) although its Sr\(^{87}/Sr^{86}\) ratio (Futa and others, this volume) is quite low. These high REE contents may be due to a small degree of partial melting of upper mantle rocks in the deep source area.

The REE patterns relative to chondritic REE concentrations show enrichment in light REE's relative to heavy REE's for nearly all samples of the Clear Lake Volcanics analyzed (fig. 19). Light-REE enrichment is generally less in basalts and greater in dacites and rhyolites. Patterns for andesites, dacites, and rhyolites are slightly concave upward. The lowest enrichment in light REE's is shown by the basalt of Caldwell Pines, which also has the lowest potassium and total REE contents. No basalt shows a pattern of depleted light REE's and flat heavy REE's as shown by oceanic ridge tholeites. REE patterns of two basalt units of the Medicine Lake Highlands area in northeastern California (Philpotts and others, 1971) are similar to the patterns of oceanic ridge tholeites. The light-REE enrichment of the Clear Lake basalts is not compatible with their generation from partial or complete melting of subducted ocean-ridge tholeitic basalts or associated oceanic crust; the Clear Lake basalts more probably came from a relatively unfractonated source. Although light-REE enrichment could be compatible with generation from subducted light-REE-enriched basalt from some oceanic islands, or associated light-REE-enriched oceanic crust, such material is volumetrically small in the oceans and in subducted oceanic slabs.

Enrichment in light REE's has been ascribed to generation from a garnet-bearing source rock (Philpotts and others, 1971), but a clinopyroxene-rich source rock could also contribute to that enrichment (Leeman, 1976). Calculated REE patterns (Zielinski and Lipman, 1976) for 40–50 percent partial melting of a trace-element-enriched source rock containing both garnet and clinopyroxene (such as eclogite or mafic granulite) are similar to REE patterns of Clear Lake basalts and basaltic andesites. The Clear Lake REE patterns also are similar to the calculated REE pat-

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terns for partial melting of garnet peridotite shown by Leeman (1976).

Positive europium (Eu) anomalies are interpreted to indicate addition of plagioclase to the melt or selective fusion of plagioclase in the area of magma generation, whereas negative Eu anomalies typically indicate loss of plagioclase from the melt or that plagioclase is residual in the area of generation. However, for the Bishop Tuff, an ash flow in the Long Valley area, California, Hildreth (1977) has shown that the rhyolitic upper part of the magma chamber contained significant gradients in Eu content, Ce/Yb ratio, and other trace elements, which were unrelated to partial melting or crystal fractionation. Thus, in silicate melts at shallow depths, other processes such as thermal-gravitational diffusion (Hildreth, 1977) may be producing Eu anomalies and changes in slope of chondrite-normalized REE patterns.

The absence of Eu anomalies in most basalts and basaltic andesites in the Clear Lake Volcanics suggests that plagioclase has not been fractionated between the source and the surface. The absence of Eu anomalies also suggests that (1) the source area lacked plagioclase, or (2) plagioclase in the source area was completely melted when basalt was generated. The light-REE enrichment and absence of Eu anomalies in Clear Lake basalts do not uniquely characterize the possible phase assemblages in the source area. These REE characteristics are qualitatively compatible with garnet peridotite, eclogite, pyroxenite, plagioclase peridotite, gabbroic granulite, or gabbro: upper mantle or lower crustal rocks. More quantitative modelling may narrow the range of possible source rocks. Although plagioclase may be stable to depths of about 60 km for gabbroic compositions and to about 35 km for peridotite compositions, the 8.0 km/s compressional wave velocity below about 22 km (Warren, 1968) suggests that plagioclase is sparse or absent at depths of basalt generation beneath the Coast Ranges.

One porphyritic plagioclase basalt has a small positive Eu anomaly (Eu/Eu* = 1.3), indicative of plagioclase enrichment. Andesites have either no Eu anomaly or small positive or negative Eu anomalies. Nearly all dacites show moderate negative Eu anomalies (Eu/Eu* = 0.5); these negative anomalies could result from loss of plagioclase phenocrysts, or from mixing of an Eu-depleted rhyolite with basalt or andesite, or from both processes. Although the present abundance of plagioclase phenocrysts in many dacites may support mixing, prior settling of plagioclase in the magma chamber also could have produced the low Eu. All samples of rhyolite show moderate to strong negative Eu anomalies, ranging from Eu/Eu* of about 0.4 to the strongest, 0.06, for rhyolite of Borax Lake. These rhyolites are likely to be products of extensive fractional crystallization and possibly some thermal-gravitational diffusion, as shown by Hildreth (1977).

Diabasic-textured inclusions are enriched in light REE's and have REE patterns that parallel those of their host rhyolites and dacites but have lower REE content in accord with their basaltic andesitic and andesitic compositions. Chondrite-normalized REE patterns of six out of seven inclusions show small negative Eu anomalies (Eu/Eu* = 0.60 to 0.83). Thus the diabasic inclusions are unlike most Clear Lake andesites and basaltic andesites which have no Eu anomalies or have less pronounced negative Eu anomalies than the inclusions. In that sense, the inclusions do not appear to be simply chilled blobs of basaltic magma, but they are likely related to high-level magmas by fractional crystallization involving plagioclase.

REE data are sparse for Great Valley, Franciscan, or other rocks at depth which could have been assimilated by the Clear Lake magmas. No data are available for Franciscan graywacke or greenstone. REE's in a serpentinitized peridotite (Frey and others, 1971) are too low to have a recognizable effect. A sandstone of the Great Valley sequence (rhyolitic SiO2 content) and a type 2 inclusion, quartz-rich schist (dacitic SiO2 content), are enriched in light REE's. The schist has a slight negative Eu anomaly, much less pronounced than the dacites or rhyolites of equivalent REE content. The sandstone shows no Eu anomaly and rather low REE concentrations, about equivalent to those in basaltic andesites. In a general way, the REE patterns permit the assimilation of schist but in detail may not fit a one-stage process. For instance, basalt or basaltic andesite plus schist could produce dacite, but magmatic plagioclase separation is needed to explain the observed Eu anomalies of dacites; an alternative explanation, that plagioclase was left in the schist during partial melting, is not likely. Assimilation of the sandstone by mafic melts to make dacite would not give the higher REE contents of dacite. Assimilation of sandstone by rhyolite could lower the REE content of the resultant rhyolite.

PLATE-TECTONIC SIGNIFICANCE

The relation of the Clear Lake Volcanics to plate tectonics is not clear. In comparison to the Cascade chain of volcanoes, the Clear Lake Volcanics and earlier eruptive centers are anomalously close to the inferred position of the offshore subduction zone that was the boundary between the North American and Farallon plates before migration of the Mendocino triple junction changed the boundary to a strike-slip
transform fault (Atwater, 1970). In timing and geographic position, these eruptive centers do not fit the usual model of melting related to active subduction of oceanic crust, but instead there is an apparent correlation between initiation of volcanism and the cessation of subduction.

Volcanism in the northern Coast Ranges has followed the northward passage of the Mendocino triple junction and attendant initiation of San Andreas transform faulting, which could have provided paths for ascent of deep magma (McLaughlin, this volume). A quiescent period of about 0.5–1 m.y. between the Sonoma Volcanics (Mankinen, 1972) and the Clear Lake Volcanics is postulated to be the time required for conduits to develop and for magma to reach the surface from the detached subducted slab or from a mantle diapir (McLaughlin, 1977b). However, three questions are unresolved. (1) If magma is already present, it should not take 0.5–1 m.y. to reach the surface in a region which has newly-developed steep faults and numerous earlier faults in part related to probable strike-slip components of subduction. Instead of lying on the main San Andreas fault zone, most of the older volcanic centers are east of the main fault, and more recent centers for Sonoma and Clear Lake volcanism align northward or northeastward from the main fault. (2) Calculations of Toksdz, Minear, and Julian (1971) indicate that 0.5–1 m.y. is too short a time to reach melting temperatures in a subducted oceanic slab at typical depths within 100 km of the subduction zone. (3) Once started, why does volcanism cease after 3 to 5 million years?

We favor a model involving a mantle heat source, or hot spot, which is fixed beneath the North American plate so that the path of volcanism could be an indication of the apparent amount and direction of motion of the North American plate or a separate sliver of that plate. The apparent path of volcanism has some superimposed clockwise rotation due to right-lateral motion on faults within the San Andreas system (Hearn and others, 1975a, 1976b). However, in contrast to the west-southwest or westerly directions of movement of the North American plate deduced from the Yellowstone and Raton, New Mexico, hot spots (Suppe and others, 1975) or the Mid-Atlantic Ridge spreading, the Clear Lake hot spot implies a southward movement of this part of the North American plate. Alternatively, the northward progression of volcanism could imply that the hot spot is moving approximately parallel to the Pacific plate and somehow is tied to that plate.

In the hot-spot model, volcanism in a new location would begin when magma from the deep hot spot reached the surface, would become more silicic as shallow magma chambers developed with accompanying assimilation and crystal fractionation, and would cease after movement of the overlying plate shut off the source of deep magma and the shallow magma chambers crystallized. Episodic plate motion could be a factor. Pressure release during initiation or intensification of transform faulting may have accelerated deep partial melting processes and facilitated the ascent of deep-source magmas.

Although there is no evidence that such a heat source is the onshore projection of an oceanic spreading ridge, as proposed by Marshak and Karig (1977) to explain volcanism anomalously close to plate boundaries, a heat source could be related to a detached segment of the East Pacific rise overridden by the North American plate. Evidence for a projected position of such a segment could lie within the near-shore area of magnetic anomalies (Mason and Raff, 1961) immediately south of the Mendocino fracture zone, where age assignment of individual anomalies has not been made (Atwater and Menard, 1970). If the Clear Lake Volcanics and earlier volcanic centers are related to a hot spot formerly on the East Pacific rise, its track could be shown by offshore seamounts or their buried expression as shallow-depth magnetic anomalies near the shore.

Low Sr isotopic ratios (0.70316–0.70356, Futa and others, this volume) for the basalts at Clear Lake favor a mantle source. REE data favor a trace-element-enriched source that is too high in total REE's and too enriched in light REE's to be subducted ocean-floor basalt, its higher pressure derivatives, or its subjacent oceanic crust. Although the REE data do not uniquely define the lithology of the source, seismic velocities suggest that rock types such as peridotite, pyroxenite, and eclogite are more likely than plagioclase-bearing rock types of lower density. Eclogitic rocks are likely major components of the deeper parts of subducted oceanic crust of the Farallon plate, but their depleted light REE's and geometric and heat-transfer considerations probably preclude recently subducted oceanic crust as a source for the volcanic rocks. Thus a garnet-clinopyroxene-bearing source would have to be related to earlier subduction of another type of crust or to other processes of mantle evolution.

**FUTURE VOLCANIC ACTIVITY**

The complex eruptive history over the past 2 million years and the 10,000-year age of the youngest eruption indicate that the Clear Lake magmatic system is not extinct and that future eruptions are likely. Such a long period of multiple volcanic events and the large volume (~1,400 km³) of the inferred magma chamber suggest that the Clear Lake system could be in a
precaldetra early evolutionary stage preliminary to major ash-flow eruptions and large-scale caldera collapse, as shown by other silicic magma systems such as Long Valley, California; Valles, New Mexico; and Yellowstone, Wyoming. Voluminous eruptions (10–200 km$^3$) of that type would be major volcanic hazards (Mullineaux, 1976) for the whole Clear Lake basin, and, if large enough, could spill over into adjacent drainage basins of the Eel, Russian, and Sacramento Rivers and Napa Valley. In addition, air-fall ash would affect a large area of several thousand square kilometers. Rhyolites of the Clear Lake Volcanics do not show the same trace-element enrichment shown by ash flows of some other major silicic systems, but they may never reach those enrichments because of regional source differences. Also, comparison with trace elements for precaldera rhyolites of other major silicic systems could have predictive significance but data are unavailable. Relative movement of the heat source at depth may preclude a duration of heating sufficient to generate the volume of volatile-rich silicic melt necessary for a large ash-flow eruption. Also, in this tectonic setting, faults of the active right-lateral stress system may tap the magma chamber or chambers often enough to prevent the buildup of volatiles necessary for a voluminous ash-flow eruption. The absence of eruptions since 0.35 m.y. ago above the present geophysically inferred magma chamber is puzzling, but it may indicate that that magma chamber is no longer being resupplied with deep-source magma and is quiescent and cooling. If the chamber were tapped again, eruptions would be silicic flows with accompanying minor pyroclastic activity, and would be vented along faults within about 10 km of Mount Hannah or farther northeast.

The Clear Lake Volcanics and Sonoma Volcanics are similar in that both are complex sequences that have an overall range from basalt to rhyolite, and larger volume of silicic than mafic rocks. However, the scarcity of pyroclastic eruptions in the Clear Lake field contrasts markedly with the Sonoma Volcanics, which contains numerous dacitic to rhyolitic ash flows (Fox and others, 1973). Sonoma ash flows are small in comparison with those in major silicic systems. Because the Sonoma Volcanics lies within the strike-slip tectonic regime, its complexity and lack of large-volume ash flows may be related to frequent tapping of the magma chambers or sources, although other factors such as chemical composition, volatile content, and depth of magma sources may have been important also.

Although future eruptions are likely in the Clear Lake field, prediction of the timing is difficult because activity has been episodic in the past. From extrapolated dates and numbers of ash beds beneath Clear Lake (Sims, 1976; Sim and Rymer, 1975), the apparent lack of eruptions in the past 10,000 years is a geologically brief lull in activity after frequent eruptions (about 34, or averaging one every 1,800 years) in the previous 60,000 years. The average interval between eruptions for the past 130,000 years has been about 2,500 years (Sims, 1976). For the period 0.35–0.65 m.y. ago, about 60 volcanic units were erupted (Hearn and others, 1976a; Donnelly, 1977), for an average interval of 5,000 years, or less if mapped units were produced by more than one eruption. Episodes of volcanic activity have typically continued for at least 0.3 m.y., so that the youngest episode which began about 0.1 m.y. ago could be in an early stage and thus could continue for another 0.2 m.y.

To the northeast of the geophysically inferred magma chamber, future eruptions would probably be mafic, similar to the youngest cinder cones and flows, although the 90,000-year-old rhyolite of Borax Lake shows that silicic eruptions are a possibility, particularly if there is a small magma chamber northeast of Clear Lake. Eruptions are likely to be located close to, beneath, or northeast of Clear Lake, especially around the east arm of the lake, near High Valley and Chalk Mountain, which are the areas of the youngest past eruptions and are above the apparent current focus of heating. A more distant area for possible future volcanism is the Wilbur Springs quicksilver district that contains a basaltic andesite dike of Pleistocene age, many thermal springs, mercury deposits, and extensive hydrothermal alteration within a small area. Eruptions near the lake are likely to be phreatomagmatic and would pose ash-fall and wave hazards to the lake shore and ash-fall hazards to areas within a few kilometers of the vent. Eruptions away from the lake would produce cinder cones and flows and would be hazardous within a few kilometers of the vents.

**GEOTHERMAL SIGNIFICANCE**

The magma chamber inferred beneath the central part of the Clear Lake Volcanics is clearly the ultimate source of heat for the Geysers steam field and for the extensive hot-water system or systems that are inferred to underlie most of the Clear Lake volcanic field (Donnelly, Goff, Thompson, and Hearn, 1976; Goff and Donnelly, 1977; Goff and others, 1977). Geothermal potential beneath the main volcanic field is promising. Within the main volcanic field, published geophysical data are not detailed enough to determine the extent of localized geothermal systems. Published geophysical data are inadequate to determine whether small satellitic magma chambers are present at depth. The young volcanic activity and thermal anomalies around the
east arm of Clear Lake, and east-northeast of Clear Lake as far east as the Wilbur Springs area, indicate geothermal potential, but the distribution of thermal springs shows the zone to be narrow and possibly not continuous. The boundary between thermal influence of the main magma chamber and current heating to the northeast is indistinct. In the northeast area, acquisition of geological, geophysical (Harrington and Verosub, this volume), and geochemical (Goff and Donnelly, 1977) data has only begun. Existing data are probably insufficient to determine subsurface structure or the presence or absence of small magma chambers.

**CONCLUSIONS**

The volcanic rocks of the Clear Lake area are the eruptive products of mantle-source heating, crustal-level fractionation and assimilation of the Great Valley, Franciscan, and underlying crustal rocks. Pyroxenite, peridotite, and eclogite are likely rock types in the deep source area. Volcanism may be a result of a mantle hot spot which has generated a series of Tertiary and Quaternary volcanic centers as the North American plate moved relatively southward across it. A geophysically inferred large (1,400 km$^2$ or greater) magma chamber beneath the Clear Lake volcanic field has existed since about 1.1 m.y. ago, or perhaps earlier, and it is the shallow-level source of geothermal heat in the Geysers-Clear Lake area. Tapping of the magma chamber and eruption of deeper magmas have been controlled in part by the stress field of the San Andreas fault system, which includes several active fault zones across and near the Clear Lake Volcanics. Future eruptions are likely to produce mafic flows and cinder cones, but possibly could produce catastrophic silicic eruptions with accompanying caldera collapse.

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