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Geology and Geochronology of the Clear Lake Volcanics, California

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ABSTRACT

The 400-km^2 Clear Lake Volcanics, of late Pliocene(?) to Holocene age, unconformably overlies rocks of mainly the Franciscan assemblage and Great Valley sequence. The nearby Geysers geothermal production area is southwest of the volcanic field.

Stratigraphic relations, magnetic polarities, and K/Ar dates have established a complex volcanic series that ranges from less that 2.5 million years (m.y.) to less than 0.03 m.y. in age and in general is progressively younger from south to north. The oldest lavas are quartz-bearing olivine basalts which extend southeast of the main field and marginally overlap Sonoma Volcanics. The main part of the field is younger than 1.0 m.y., and the central part is younger than 0.5 m.y. The youngest rhyolite is 0.088 ± 0.013 m.y. The most recent activity, as young as about 0.010 m.y., produced basaltic to andesitic cinder cones and maar-type pyroclastic deposits. The sequences suggest changes in magma composition from basalt or andesite through dacite to rhyolite, although dacites are missing from some sequences.

The many normal faults in the field trend northeast, northwest, and north-northwest. The youngest faults trend north-northwest or northwest, approximately parallel to the San Andreas system. Inferred strike-slip offset on one northwest-trending fault suggests movement, if continuous, at an average rate of 1 mm/yr for the past 0.5 m.y. Earthquakes within the volcanic field and Clear Lake basin are suggestive of current deformation.

Gravity and resistivity lows over the volcanic field can be interpreted as being related to an underlying partially fluid magma chamber. Repeated silicic volcanism, lack of ash-flow tuffs, and lack of large-scale caldera collapse suggest that the volcanic system is in an early evolutionary stage. The size and youth of the volcanic system and the distribution of thermal springs and wells imply that the volcanic field and its surroundings have considerable geothermal potential.

INTRODUCTION

The Clear Lake Volcanics of late Pliocene(?) to Holocene age covers 400 sq km about 150 km north of San Francisco in the Coast Ranges of California. (The Clear Lake Volcanic series of Brice [1953] is herein adopted for U.S. Geological Survey usage as Clear Lake Volcanics as used by California Department of Water Resources [1962].) The Geysers geothermal production area is beyond the southwest border of the field. This report presents preliminary results of a continuing program of detailed geologic mapping, geochronology, geochemistry, and geophysics. About two-thirds of the field has been mapped in detail at 1:24 000 scale (Hearn, Donnelly, and Goff, unpub. data); the remainder has been mapped by reconnaissance and photogeology.

Several previous investigators have contributed to the knowledge of this volcanic area and its surroundings, beginning particularly with Anderson's (1936) perceptive study. More recent studies were done by Brice (1953), California Department of Water Resources (1962), Hodges (1966), McNitt (1968a, b, c), Swe and Dickinson (1970), and Berkland (1972). McLaughlin (1974) has thoroughly mapped the Franciscan terrane in the vicinity of The Geysers geothermal field. Sims and Rymer (1974, 1975a and b) are studying the lake-bottom sediments and structural control of the Clear Lake basin.

Considerable geophysical information available for the Geysers-Clear Lake area consists of aeromagnetic data (U.S. Geological Survey, 1973), gravity and magnetic data (Chapman, 1966, 1975; Isherwood, 1975), and electrical data (Stanley, Jackson, and Hearn, 1973).

Hamilton and Muffler (1972) discussed earthquakes of local origin in The Geysers geothermal field. Investigation of deep and shallow thermal fluids (White and Roberson, 1962; Barnes et al., 1973) are continuing. Garrison (1972) published a recent summary of geology and reservoir characteristics of the geothermal production area.

GEOLOGIC SETTING

The Clear Lake Volcanics overlie rocks of the assemblage of the Franciscan Formation of Late Jurassic to Eocene age, the Great Valley sequence of Late Jurassic to Late Cretaceous age, sedimentary rocks of Paleocene and Eocene age, and the Cache Formation as used by Brice (1953) of Pliocene and Pleistocene age. The main part of the Clear Lake volcanic field occupies the southern part of the Clear Lake topographic basin and extends southward toward the crest of the Mayacmas Range. Outliers of the field include: an area of quartz-bearing olivine basalt flows which extends southeastward 35-40 km from the east edge, isolated small areas of extrusive and intrusive rocks of probable Clear Lake volcanic affinity which occur as far as 16 km to the northeast, and several isolated small areas of volcanic rocks of undetermined affinity to the south and southwest.

The Sonoma Volcanics of Pliocene age extend from the San Francisco Bay area to the vicinity of Mt. St. Helena, 20 km southeast of The Geysers geothermal production area. Published ages on the Sonoma volcanics are 5.3 m.y. to 2.9 m.y. The youngest date is on a welded tuff at Mt. St. Helena at the northern end of the field (Mankinen, 1972), closest to the Clear Lake Volcanics. The Clear Lake Volcanics, with the exception of the early quartz-bearing olivine basalts, are geographically separate from the Sonoma Volcanics, and present data show no significant overlap in ages. However, the ages of isolated patches of volcanic rocks between Mt. St. Helena and Cobb Mountain are unknown.

The Clear Lake topographic basin is superimposed on a broad northwest-trending zone of complexly folded thrust sheets of Great Valley sequence and serpentinized mafic and ultramafic rocks which have been thrust across the structurally complex Franciscan assemblage (Swe and Dickinson, 1970; Berkland, 1973). The basal faults have been interpreted by those authors as equivalent to the Coast Range thrust which is the major boundary between Great Valley sequence the Franciscan assemblage. The basal faults have been interpreted by others (Maxwell, 1974) as relatively minor displacements on the border of nearly in situ local basins of deposition of Great Valley-type sediments. The southeastern part of the volcanic field unconformably overlies thrust sheets of Great Valley sequence and Paleocene and Eocene sedimentary rocks. The northwest limit of the allocthonous Great Valley sequence is concealed beneath the volcanic field or beneath lake sediments. The next occurrence of Great Valley sequence to the northwest, the Middle Mountain block (Berkland, 1973), is isolated north of Clear Lake.

The Cache Formation, most of which predates the Clear Lake Volcanics, consists of fresh-water sedimentary deposits which filled an irregular fault-bounded basin largely east of, and not coincident with, the present Clear Lake basin. Clastic and volcaniclastic deposits that occur beneath, within, and near to the Clear Lake Volcanics have been correlated with the upper part of the Cache Formation by previous workers (Brice, 1953; McNitt, 1968a; Hodges, 1966; Swe and Dickinson, 1970). However, many of those clastic deposits are isolated from the type Cache Formation and are dissimilar to it in lithology (M. J. Rymer, personal commun.). Also, many of those deposits are probably younger than any part of the type Cache Formation.

The Clear Lake topographic basin is in part a structural basin, partially delineated by faults of north, north-northwest, northwest, and west trend (Sims and Rymer, 1974, 1975b). The basin has been partially filled by lake and flood plain deposits which are interbedded at depth with flows and pyroclastic deposits of the Clear Lake Volcanics. Sedimentary deposits beneath the present Clear Lake represent a probably continuous record of sedimentation for at least the last 150 000 years (core 4, Sims and Rymer, 1975).

CLEAR LAKE VOLCANICS

The Clear Lake Volcanics consist of basalt, andesite, dacite, and rhyolite, which occur as domes, flows, and pyroclastic deposits in a structurally and chronologically complex sequence (Figure 1). Rock names in this report are based mainly on field identifications and a small number of chemical analyses and are thus tentative until more chemical data are available. Rocks termed basalt may actually be basaltic andesite or andesite, chemically. The term rhyodacite has been difficult to apply in the field; many rocks that may be of rhyodacite composition are grouped with the dacites.

The Clear Lake Volcanics characteristically contain quartz not only as phenocrysts in the more silicic types but as 1 mm-15 cm rounded to subangular commonly resorbed grains of uncertain origin in mafic rock types. All the basalts contain olivine, in amounts ranging from a trace to about 10%. Andesites typically contain phenocrysts of plagioclase and orthopyroxene, with or without clinopyroxene, and vary widely in pyroxene content. The many dacites range from highly porphyritic to sparsely porphyritic varieties and contain phenocrysts of plagioclase, clinopyroxene, orthopyroxene, and quartz; many contain sanidine. Most varieties also possess small amounts of biotite or hornblende or both. Some sparsely porphyritic varieties have widespread glassy chilled facies. Two types of rhyolites are present, biotite-bearing and nearly biotite-free. Biotite rhyolites are typically crystal rich (15-30% quartz and feldspar phenocrysts), tend to be perlitic, and have formed significant pyroclastic deposits. Biotite-free rhyolites are typically crystal poor (3% or less phenocrysts) and show widespread glassy obsidian facies on flow borders. Only one biotite-free rhyolite formed a large volume of pyroclastic material. No rhyolitic ash-flow deposits are present in the Clear Lake field. The preserved volume of volcanic rocks that have compositions more silicic than andesite is about 35 cubic km if the Mt. Konocti pile bottoms at lake level, and 50 cubic km if it extends 300 m below lake level. The preserved volume of basalt and andesite is about 10 to 15 cubic kilometers.

GEOCHRONOLOGY

K/Ar dates range from about 2.5 m.y. to 0.03 m.y. or less and are in good agreement with magnetic-polarity determinations and known stratigraphic relations (Table 1). The main part of the field is younger than 1.0 m.y., and much of the central part is younger than 0.5 m.y. In general, the volcanic rocks are progressively younger northward through the field.

The oldest dated unit is the 2.46 ± 0.69 m.y. isolated olivine basalt at Caldwell Pines (Figure 1). Its affinity with

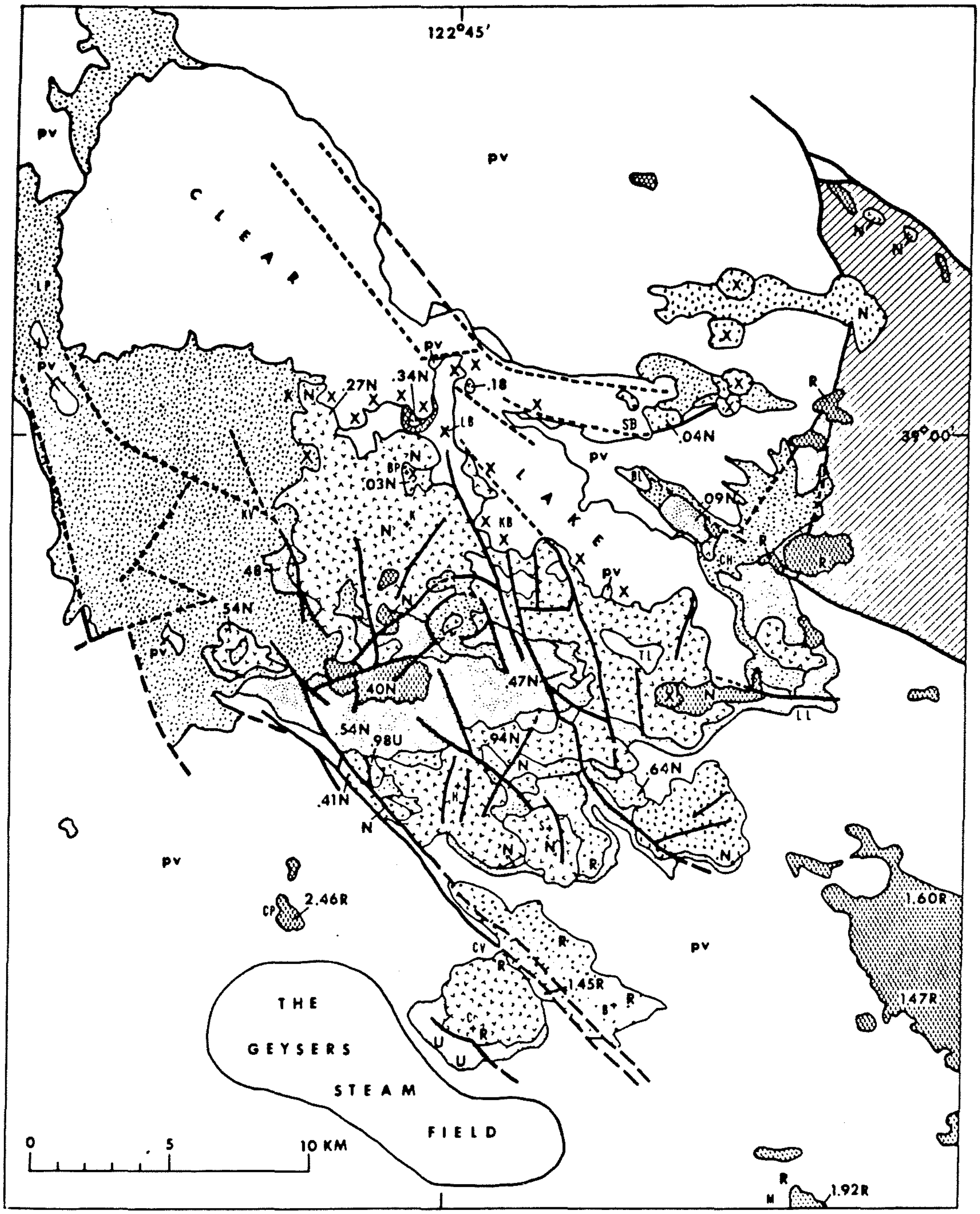

Figure 1. Generalized geologic map of Clear Lake volcanic field, showing K/Ar ages and magnetic polarities. Lake and alluvial deposits are shown only near Clear Lake. Order of volcanic units in explanation is not sequence of eruption. Lateral extent of cinder cones shown where associated with flows. Contacts shown within a single rock type are between flows of different age and/or magnetic polarity. Faults dashed where inferred, dotted where concealed. Geology in part modified from Brice (1953), Lake County Flood Control and Water Conservation District (1967), McNitt (1968a, b, c), and Sims and Rymer (in press). 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 (modified from Brice, 1952).

Table 1. Eruptive sequence, K/Ar ages, magnetic polarities and SiO_2 compositions of Clear Lake volcanics.

SiO_2 as % of weight	Rock type: Basalt	Rock type: Andesite	Rock type: Dacite	Rock type: Rhyolite	K/Ar age (m.y.) W–Whole rock B–Biotite S–Sanidine	Remanent magnetic polarity N–Normal R–Reverse U-Unique, low angle	Polarity event	Polarity epoch
55–62	o	o						Brunhes normal
[55–57	o	o			0.30 ± .03W	N		
57		o				N		
56–57		o			0.04 ± .04W	N		
76–77				o	0.088 ± .013W*	N		
66			o					
55	o							
[68			o		0.18 ± .02S			
			o			N		
68			o		0.27 ± .04S	N		
57	o							
[			o		0.34 ± .01S**	N		
			o			N		
			o			N		
71				o				
73				o				
	o					N		
				o				
			o					
		o						
				o				
56–59	o				0.40 ± .18W	N		
60		o			0.41 ± .04W	N		
72–74				o	0.48 ± .04S 0.48 ± .11B			
72–74				o	0.466 ± .015W*	N		
74–75				o	0.536 ± .016W*	N		
[			o		0.54 ± .03S	N		
			o					
			o				Jaramillo	Matuyama reversed
		o						
61–62		o			0.64 ± .04W	N		
67–70			o		0.94 ± .17W	N		
67			o		0.98 ± .22W	U		
62		o				R		
				o				
			o			R		
			o					
[					1.1?**	R		
72				o		U		
60		o			1.45 ± .04W	R		
57	o				1.47 ± .29W	R		
	o				1.60 ± .53W	R		
	o				1.92 ± .77W	R		

*K/Ar by J. Von Essen and A. Atkinson, K analysis by L. Schlocker, U.S. Geological Survey. Other K/Ar ages by J. M. Donnelly, K analyses by J. Hampel.
**C. Wahrhaftig and G. H. Curtis, unpublished data.
Note: Lines connect units which have close spatial relations. Brackets designate groups of units of unknown relative age.

the Clear Lake Volcanics is uncertain; it may be a northern outlier of the older Sonoma Volcanics. The widespread quartz-bearing olivine basalts southeast of the main part of the Clear Lake field give ages of 1.47 ± 0.29, 1.60 ± 0.53, and 1.92 ± 0.77 m.y., and marginally overlap Sonoma Volcanics southeast of Middletown. Although the absolute range of age of these olivine basalts is uncertain, their consistent reverse magnetic polarity suggests that they are about 2.4 m.y. to 1.8 m.y. old or 1.6 m.y. to 0.7 m.y. old. To the west of the basalts, eruptions of andesite flows of Boggs Mountain at 1.45 ± 0.04 m.y. were followed by more silicic eruptions of dacite and rhyolite at about 1.1 m.y. at Cobb Mountain.

A widespread obsidian-bearing rhyolitic tuff and tuff breccia underlies much of the southern edge of the volcanic field, and was erupted from a source northeast of Seigler Mountain. This tuff was assigned to the Cache Formation by Brice (1953), but its equivalent is not known in the type Cache Formation. Subsequent eruptions produced a variety of andesites and dacites from vents in the southern and central parts of the field. Two petrographically similar silicic dacites, which have been dated at 0.94 ± 0.17 m.y. and 0.98 ± 0.22 m.y. and show normal and unique low-angle magnetic polarity respectively, probably record the 0.89 m.y.-0.95 m.y. Jaramillo normal magnetic event.

About 0.5 m.y. ago, a major period of silicic volcanism began in the central part of the field with the eruption of about 4 cubic km of sparsely porphyritic rhyolite, dated at 0.48 ± 0.04 m.y. In the interval 0.48 m.y. to about 0.3 m.y., eruption of small volumes of biotite rhyolite (dominantly pyroclastic) alternated with eruptions of small volumes of basalt and olivine basalt. These local basalts and biotite rhyolites, and the earlier widespread biotite-free rhyolite, were partially covered by the voluminous eruptions of dacite which built 1000 m high Mt. Konocti and created a ridge of coalesced dacite domes and flows aligned east-southeast from Mt. Konocti. On the southwest edge of Mt. Konocti, dacite overlies biotite rhyolite of 0.48 m.y. age. On the north side, a dacite dated at 0.34 m.y. is successively overlain by olivine basalt and by several hundred meters of younger dacite.

The domal dacitic accumulations of Mt. Hannah and Seigler Mountain seem to be exceptions to the generally older ages in the southern part of the field. Their topographic expression and presence of vesicular glassy facies indicate that both were probably built less than 0.5 m.y. ago.

The youngest silicic eruptions dated so far are a biotite dacite at about 0.18 ± 0.02 m.y., at lake level northeast of Mt. Konocti, and a rhyolitic obsidian southeast of Borax Lake, at 0.088 ± 0.013 m.y. The rhyolite of Borax Lake is chemically related to an adjacent earlier olivine dacite flow (Bowman, Asaro, and Perlman, 1973). An adjacent, and presumably underlying, subdued cinder cone of olivine-bearing basalt may represent an even older, parental basaltic magma which forms part of the variation series.

The most recent eruptive activity was basaltic to andesitic in composition and was in part phreatic. This activity produced the cinder cone and flow at Buckingham Peak, dated at 0.03 ± 0.03 m.y., and produced cinder cones and flows along a N.10°E. trend across the east arms of Clear Lake. The andesite flow at Sulphur Bank (White and Roberson, 1962) yielded a K/Ar date of 0.04 ± 0.04 m.y. Phreatic eruptions along the lake shore have left a widespread blanket of pyroclastic deposits and localized base-surge deposits, for example in the tuff ring surrounding the Little Borax Lake maar. This maar is younger than about 0.03 m.y., as its final eruption removed most of a large landslide which cut away about half of the cinder cone at Buckingham Peak.

The series of young basaltic to andesitic eruptions is probably represented by the many mafic ash beds in cores of sediments beneath Clear Lake (Sims and Rymer, 1975). The youngest ash recognized in a core from the southeastern arm of Clear Lake is about 10 000 years old (core 7, Sims and Rymer, 1975). Continuation of volcanic activity to such recent time indicates that there is potential for future eruptions.

The tentative eruptive sequence suggests that the composition of erupted magma changed from basalt or andesite through dacite to rhyolite, and from basalt or andesite to rhyolite without apparent intermediate rock types (Table 1). From the limited present data, such changes in composition show both extended and compressed time spans. Changes in magma compositions, and the large volume of silicic rocks, indicate that major differentiation or melting has occurred, which in turn implies a large magma chamber source for the volcanic system.

STRUCTURE

Faults in the Clear Lake Volcanic field trend from northeast to northwest, the northwest trend being dominant. The youngest faults trend northwest which is also parallel to the general structure grain of the Coast Ranges and parallel to the San Andreas fault system. Two prominent fault zones follow this trend—the Konocti Bay fault zone which extends east of Seigler Mountain to the northeast side of Mt. Konocti, and the Cobb Valley fault zone along the southwest side of Boggs Mountain. Although most faults are normal faults, several northwest- to north-northwest-trending faults show features suggestive of right-lateral strike slip displacement, for example, in the fault zone southeast of Kelseyville, locally within the Konocti Bay fault zone, and along much of the Cobb Valley fault zone. In the last zone, a young age of strike-slip movement is suggested by offset topographic features. Offset of contacts of volcanic units of 0.5 m.y. and younger age suggests that movement, if continuous, has been at a rate of about 1 mm/year for the past 0.5 m.y.

Active deformation within the volcanic field and within the Clear Lake structural basin is indicated by felt earthquakes, of magnitude as great as 4.6. Approximate locations of epicenters (Hamilton and Muffler, 1972; Chapman, 1975) suggest that some of the earthquakes are ocurring close to the Cobb Valley fault zone. Some locally felt earthquakes are most intense south of Konocti Bay and are possibly associated with the Konocti Bay fault zone. Local earthquakes also may be associated with the faults that bound the Clear Lake Basin. McLaughlin and Stanley (1975) have found that microearthquakes are associated with a north-northwest-trending fault zone in The Geysers steam field. Ongoing seismic studies hopefully will enable more precise location of sources and mechanisms of local earthquakes; the monitoring of changes in level and horizontal distances (Lofgren, 1973) will characterize current deformation and tilting in the Clear Lake/Geysers area.

Although parts of the volcanic field show local subsidence and the Clear Lake structural basin is probably continuing to subside, evidence for large-scale caldera collapse is lacking. The largest local circular collapse feature is the 1.6 km diameter basin southeast of Mt. Konocti. Although the shape of the northern part of Clear Lake and some adjacent faults are suggestive of partial control by circular collapse, data are not sufficient to determine the validity of such a subsidence pattern.

GEOPHYSICAL STUDIES

Gravity data delineate a circular 25-30 mgal low, 30 km in diameter, centered at Mt. Hannah. The circular shape of the gravity low, superimposed upon the structural trend of the Coast Ranges, indicates that the low is not related to density contrasts of structural blocks having northwest-southeast elongation. This gravity low has been interpreted as the expression of a magma chamber at a depth of 10 km or less (Chapman, 1966, 1975; Isherwood, 1975).

The occurrences of thermal springs and wells in and within about 20 km of the Clear Lake volcanic field imply that there is an anomalously hot mass at depth. Electrical surveys show a well-defined resistivity low which is beneath the south-central part of the volcanic field, is in part coincident with the gravity low, and extends to at least 5 km depth (Stanley, Jackson and Hearn, 1973). The resistivity low can be interpreted as being due to a thick section of marine shale or to the presence of hot saline fluids, or a combination of the two; however, limited drill hole data and the structural complexity of Great Valley and Franciscan rocks beneath and southeast of the volcanic field preclude the presence of a marine shale several thousand meters thick. Thus, the resistivity low is probably produced by combined effects of elevated temperature and salinity of water above a heat source at depth—a large mass of hot rock or magma.

CONCLUSIONS

The possible existence of a magma chamber beneath the Clear Lake volcanic field is supported by the volume of silicic volcanic rocks, by evidence of differentiation, and by the geophysical anomalies. The age, inferred depth, and volume of such a magma chamber indicate that the volcanic field and surrounding area have geothermal potential (Smith and Shaw, 1973). Confirmation of a magma chamber will depend on future data from drilling and from indirect deep-sensing methods.

By comparison with other silicic volcanic fields, the Clear Lake field is believed to be in an early stage of evolution. It has erupted a significant volume of silicic magma, has been active within the last 10 000-20 000 years, and has not yet reached a stage of voluminous ash-flow eruption and large-scale caldera collapse. However, if a regional strike-slip deformation parallel to the San Andreas system is being superimposed on localized deformation related to a magma chamber, the magmatic system may not be able to proceed through the stages of growth shown by other systems, but instead may be tapped more frequently by smaller eruptions. That some such process is operating in the Clear Lake field is suggested by the complex repetitive cycles of mafic-silicic eruptions. If the geometry of the magma chamber is continually changing and its roof is fracturing as a result of regional stresses, a progressive accumulation of gas-rich silicic differentiate, necessary for voluminous ash-flow eruption, may not occur.

The apparent northward decrease in age in both the Sonoma and Clear Lake volcanic fields suggests the possibility that both are surface manifestations of deep magma generation by the same thermal anomaly or hot spot in the mantle. The direction of migration of volcanic activity implies that, relative to the hot spot, the North American plate has moved south-southeast or southeast. The actual direction of migration of volcanic activity may have been modified by successive movement on right-lateral strike-slip faults, which would have produced an apparent clockwise rotation, from a northwest direction to a more northerly direction.

The geothermal potential of the Clear Lake volcanic field and its surroundings is strongly indicated by the size and youth of the field, the presence of The Geysers production area, the inferred presence of a shallow subjacent magma chamber, and the distribution of thermal springs and wells. Further exploration for geothermal resources will better define the hydrology, heat flow, and vertical dimensions of the volcanic system.

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