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PETROLOGIC CONSIDERATIONS FOR HOT DRY ROCK GEOTHERMAL SITE SELECTION IN THE CLEAR LAKE REGION, CALIFORNIA

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ABSTRACT

The Clear Lake area is well known for anomalous heat flow, thermal springs, hydrothermal mineral deposits, and Quaternary volcanism. These factors, along with the apparent lack of a large reservoir of geothermal fluid north of the Collayomi fault make the Clear Lake area an attractive target for hot dry rock (HDR) geothermal development. Petrologic considerations provide some constraints on site selection for HDR development. Spatial and temporal trends in volcanism in the Coast Ranges indicate that magmatism has migrated to the north with time, paralleling passage of the Mendocino triple junction and propagation of the San Andreas fault (Johnson and O'Neil, 1984; Fox, 1985). Volcanism in the region may have resulted from upwelling of hot asthenosphere along the southern margin of the subducted segment of the Gorda plate (Dickinson and Synder, 1979).

Spatial and temporal trends of volcanism within the Clear Lake volcanic field are similar to larger-scale trends of Neogene volcanism in the Coast Ranges. Volcanism (especially for silicic compositions) shows a general migration to the north over the ~2 Ma history of the field, with the youngest two silicic centers located at Mt. Konocti and Borax Lake. The Mt. Konocti system (active from ~0.6 to 0.3 Ma) was large and long-lived, whereas the Borax Lake system is much smaller but younger (0.09 Ma). Remnants of silicic magma bodies under Mt. Konocti may be in the latter stages of cooling, whereas a magma body centered under Borax Lake may be in the early stages of development. The existence of an upper crustal silicic magma body of under Borax Lake has yet to be demonstrated by passive geophysics, however, subsurface temperatures in the area are as high (>200°C at 2000 m) as those beneath the Mt. Konocti area. Based on petrologic considerations alone, the Mt. Konocti-Borax Lake area appears to be the most logical choice for HDR geothermal development in the region.

INTRODUCTION

The Clear Lake area is well known for its geothermal manifestations and hydrothermal mineral deposits (White and Roberson, 1962; Goff et al., 1977; Hearn et al., 1981; Peters, 1991). The anomalous heat flow ($\geq$170 mW/m^2), high conductive thermal gradients (~80-120°C/km), and lack of evidence for a large reservoir of geothermal fluid north of The Geysers make the Clear Lake area a prospective site for HDR development (Goff and Decker, 1983; Burns, 1991). In this paper we briefly review petrologic and regional tectonic factors bearing on selection of a site for Hot Dry Rock (HDR) geothermal development in the Clear Lake area. This analysis is based primarily on detailed study of the silicic volcanic centers at Clear Lake and their implications for the nature of the magmatic system at depth (Stimac et al, 1990; Stimac, 1991; Stimac and Pearce, in press). Although consideration of these factors does not allow recommendation of a specific drilling site, they do suggest that a site in the Mt. Konocti-Borax Lake area is likely to intercept near-surface magmatic heat. This conclusion is somewhat in conflict with the results of gravity (Isherwood, 1981) and seismic studies (Iyer et al., 1981; Eberhart-Phillips, 1986) that suggest the presence of a large magma chamber centered beneath the southern part of the Clear Lake volcanic field (Mt. Hannah area) rather than the northern portion of the field.

REGIONAL TECTONIC SETTING AND MAGMATIC HISTORY

Clear Lake is located in the northern Coast Ranges about 135 km north of San Francisco in a broad zone of deformation related to the San Andreas Transform (McLaughlin, 1981). The Clear Lake Basin (Sims, 1988) is a transtentional basin active since about 0.6 Ma (Hearn et al., 1988). The Clear Lake volcanic field is the northernmost of a series of volcanic centers thought to be associated with the passage of the Mendocino triple junction (Johnson and O'Neil, 1984; Fox, 1985) (Fig. 1). It has been proposed that volcanism in the region followed development of a "no slab window" resulting from northward migration of the triple junction (Dickinson and Synder, 1979) (Fig. 2). Upwelling of hot asthenosphere in the wake of this migration provides a plausible explanation for: (1) regional northward migration of volcanism, (2) the timing of volcanism in relation to the estimated position of the triple junction, and (3) very high regional heat flow (Lachenbruch and Sass, 1980; Liu and Furlong, 1992). The Clear Lake volcanic field is the northernmost manifestation of tectonically driven magmatism in the region, however, seismic tomography studies define a region of low velocity in the middle and upper crust about 65 km north of Clear Lake (Benz et al., 1992). This may indicate that the initial stage of mafic magma injection is occurring in that area (Benz et al., 1992; Liu and Furlong, 1992).

TECTONIC SETTING AND MAGMATIC HISTORY AT CLEAR LAKE

In addition to the regional control on magmatism imposed by migration of the Mendocino triple junction, local tectonic factors also appear to focus volcanism. For example there is an association between volcanism and formation of the Clear Lake Basin (Hearn et al., 1988). Part of the Clear Lake Basin is bounded by structures that may have also facilitated the ascent of silicic magmas.

Spatial and temporal trends of volcanism within the Clear Lake volcanic field have a similar pattern to larger scale trends of volcanism in the Coast Ranges. Volcanic rocks at Clear Lake with ages from 2.1 to 0.01 Ma (Donnelly-Nolan et al., 1981) range in composition from basalt to rhyolite. Based on regional mapping and extensive K-Ar dating of the Clear Lake volcanics, Donnelly-Nolan et al. (1981) defined four discrete periods of volcanism showing a general migration to the north (Fig. 3). The northward migration is especially clear for silicic volcanism.

Mafic magmas have erupted throughout the lifespan of the system (Hearn et al., 1976; Hearn et al., 1981), but the distribution of mafic vents was widespread in the initial episode (Fig. 3A). This is thought to reflect the fact that magmatism in the area is fundamentally basaltic in origin. Following this initial episode, the locus of mafic volcanism has shifted northward through time, with the youngest mafic activity occurring in two subparallel north-trending belts that straddle the eastern side of Clear Lake (Hearn et al., 1981). The linear arrangement of vents along these trends indicates that mafic magmas reach the surface along faults. The chemistry and petrology of young mafic lavas suggests that they are variably contaminated by interaction with crustal rocks (Stimac, 1991; Stimac and Goff, unpub. data).

Silicic Centers

Silicic volcanism shows an even clearer migration to the north with time (Fig. 3B). The oldest large silicic center is located at Cobb Mountain, with successively younger rhyolitic and dacitic centers located in the areas of Mt. Hannah, at Mt. Konocti, and at Borax Lake. The youngest silicic lava was erupted near Borax Lake at about 0.09 Ma (obsidian whole-rock date by Donnelly-Nolan et al., 1981). Eruption of the Borax Lake rhyolite was preceded by numerous eruptions of mafic magma in the area (Fig. 3B), and was directly preceded by eruption of the basalt of Arrowhead Road and dacite of Clear Lake Park. The mineralogy, texture, chemistry, and isotopic signature of the rhyolite of Borax Lake indicates it may represent a crustal melt superheated by interaction with more mafic magma (Patterson-Latham, 1985; Stimac and Goff, unpub. data). It is not known if an upper crustal silicic magma body currently resides beneath the Borax Lake area, but a 7-km-long electrical resistivity low of 10Ωm straddles the area between Sulphur Bank Mine and Borax Lake (Stanley et al., 1973), and subsurface temperatures in several wells are certainly high (>200°C at 2000 m)(Goff and Decker, 1983; Beall, 1985).

A much larger volume of silicic lava was erupted from 0.65 to 0.30 Ma in the Mt. Konocti area. Establishment of a large silicic magma reservoir centered under Mt. Konocti was signaled by eruption of about 6 km^3 of rhyolitic magma (rhyolite of Thurston Creek) from a series of vents at ~0.6 Ma. The resulting lavas are chemically and texturally very similar, indicating that they were erupted from a single magma source (Stimac et al., 1990). This eruptive period culminated with extrusion of about 35 km^3 of mixed dacite from 0.4 to 0.3 Ma (Donnelly-Nolan et al., 1981). Textural and chemical evidence indicates that these dacites were formed by mixing of mafic magma with crystal-rich rhyolitic magma (Stimac, 1991; Stimac and Pearce, in press). The wide distribution of silicic vents and large number of separate dacitic eruptions during this time period imply episodic resupply of mafic magma to a cluster of upper-crustal silicic magma bodies. It would also imply a complex cooling history for this large magmatic system. Hypothetical cross sections through the magmatic system at successive stages in its development are given in Figure 4. This model is based on detailed study of lava distribution, chemistry, and texture (Stimac, 1991), as well as geophysical evidence (Isherwood, 1981; Iyer et al., 1981; Eberhart-Philllips, 1986) that indicates that the current magma bodies at Clear Lake have their tops at about 7 km depth.

MINERALOGICAL CONSTRAINTS ON MAGMATIC TEMPERATURES AND PRESSURES

The mineralogy and texture of lavas erupted at Clear Lake provide some constraints on the temperature of their source magma bodies. For example, the composition of certain minerals or mineral pairs are sensitive indicators of their temperature of formation (Roeder and Emslie, 1968; Davidson and Lindsley, 1985; Fuhrman and Lindsley, 1988). Temperature estimates based on these geothermometers are given (Table 1) for magmas ranging in composition from basaltic andesite to rhyolite (Stimac, 1991). Based on olivine-liquid thermometry, basaltic andesite lavas at Clear Lake were erupted at temperatures of ~1000 to 1150°C. Rhyolitic magmas show a wider range in temperature, related to their degree of crystallinity, and residence time in the upper crust. Based on two-pyroxene thermometery, crystal-poor rhyolites such as the rhyolite of Thurston Creek, formed at temperatures of ~900°C, whereas based on two-feldspar and two-pyroxene assemblages crystal-rich rhyolites formed at temperatures as low as 700°C. Dacitic magmas representing mixtures of rhyolitic and mafic magmas probably reached thermal equilibrium at temperatures of 800-900°C shortly before eruption (Stimac, 1991). Although the thermometers used are relatively insensitive to the pressure of equilibration, utilizing pressures of 2 kb (~6 km depth) yield reasonable results for all thermometers.

Xenoliths of crustal rocks in mafic lavas provide some estimate of the depth of crust-magma interaction in the region. Xenolith mineral assemblages including garnet, sillimanite, cordierite, orthopyroxene, and biotite suggest pressures of formation ranging from ~3 to 6 kb, or 9 to 18 km depth (Stimac and Goff, unpub. data; Glassley, unpub. data). These preliminary estimates suggest that crustal assimilation by mafic magmas occurred primarily at lower to mid-crustal depths.

THE NATURE OF THE MAGMATIC SYSTEM - A WORKING MODEL

Numerous lines of petrologic and geophysical evidence are consistent with a simplified two-level system of magmatic activity at Clear Lake. A deep-level system developed by dike-injection of basaltic magma into the lower to middle crust, as a result of upwelling of hot asthenosphere in the wake of passage of the Mendocino triple junction. Large-scale ponding of basaltic magma in the deep crust appears to have fostered high-grade metamorphism and partial melting of lower- to mid-crustal rocks. This is indicated both by the presence of xenoliths of high-grade metamorphic rocks in contaminated basaltic andesite and andesite lavas, and by the isotopic and trace element chemistry of silicic lavas, which reflect a large crustal contribution (Stimac, 1991).

In areas of intense mafic injection, the scale of silicic melt generation may be large enough for silicic magmas to rise to upper crustal levels as diapirs or dikes along fractures, where they stall due to neutral buoyancy. Once silicic magmatic systems are established in the upper crust, they inhibit passage of incoming mafic magmas by acting as density filters (Hildreth, 1981). In such cases, subsequent injections of mafic magma pond beneath the silicic reservoirs or erupt at their margins. Continued episodic injection of mafic magma into the base of the silicic system produces mixed dacites and may provide sufficient heat to sustain the system for long periods of time. Once mafic input ceases, however, the system will eventually cool. This process appears to have operated at Mt. Konocti, leading to numerous eruptions of mixed dacite lava (Stimac, 1991) at about 0.4 to 0.3 Ma. High heat flow in the Mt. Konocti area indicates that the magmatic system is still cooling (Goff and Decker, 1983).

If this general model for magmatism in the Clear Lake area is correct, then mafic and silicic volcanism in the Borax Lake area may be a manifestation of northward-stepping basaltic dike injection at depth, with the Borax Lake rhyolite representing the first silicic melt generated. The area encompassing the southeast part of the lake, Sulphur Bank Mine, Borax Lake, and High Valley contains the youngest mafic eruptions in the Clear Lake volcanic field (0.04 to 0.01

Ma) (Sims et al., 1981), and subsurface temperatures as high as those in the Mt. Konocti area (>200°C at 2000 m)(Goff and Decker, 1983; Beall, 1985). It is possible that the locus of basaltic injection in the region has extended north of the Clear Lake area (Liu and Furlong, 1992), but has not yet produced volcanism.

CONCLUSIONS

Regional geologic and tectonic considerations are consistent with a model of a northward migration of mantle-derived basaltic dike injection into the crust. Injection of mantle-derived basaltic magmas into the lower crust appears to trigger local melting and eventual establishment of upper crustal silicic magma bodies. Continued mafic input sustains upper crustal magma bodies and leads to production of mixed magmas. The most recent large silicic system gave rise to the lavas of the Mt. Konocti area from 0.6 to 0.3 Ma, whereas younger, but smaller-volume silicic activity occurred in the Borax Lake area (0.09 Ma). Remnants of silicic magma bodies near Mt. Konocti may be in the latter stages of cooling, whereas a magma body centered under Borax Lake may be in the early stages of development. Based on regional tectonic and geologic factors alone, the Mt. Konocti-Borax Lake area appears to be the most logical choice for HDR geothermal development in the region.

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Table 1. Estimates of Equilibration Temperatures for Various Minerals and Mineral Assemblages

Unit	Two-Pyroxene Thermometer (Davidson and Lindsley, 1985)		Olivine Thermometry (Roeder and Emslie, 1970)		Two-Feldspar Thermometer (Fuhrman and Lindsley, 1986)
RT	898-971		-	-	-
RT/QMI	946-1082		1047-1065	(Fo82-83)	-
RR	-		-	-	644-671
RR/QMI	-		1020-1065	(Fo79-81)	-
BK	-		1115-1150	(Fo86-88)	-
BM	-		996-1032	(Fo66-69)	-
	Mafic	Silicic			
DSB	-	-			736-756
DBR	1078(CA) 1084-1108(QMI)	691-697			
DKB	919-1064(CA)	-			736-746
DV	1010-1012(CA)	651-858			
DT	923-1041(QMI)	-			
XL-RICH RHYOLITES	-	-			696-763

All temperatures in degrees Centigrade.

Unit Names: RT, rhyolite of Thurston Creek; RR, rhyolite of Red Hill Road; BK, basaltic andesites of Mt. Konocti; BM, basaltic andesite of McIntire Creek; DSB, DBR, DKB are dacites of Mt. Konocti; DV and DT are dacites of Thurston Lake.

Dacites have two distinct mineral assemblages that equilibrated in mafic and silicic magmas. Equilibration temperatures of mixed dacites are estimated at from 800-900 degrees C.

CA=crystal aggregate; QMI=quenched mafic inclusion.

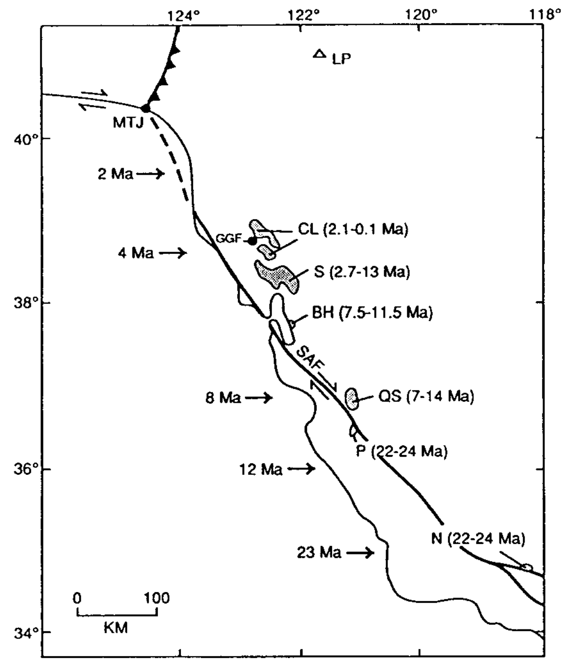
FIGURE CAPTIONS

Fig. 1. Locations and ages of volcanic fields in the Coast Ranges in relation to the San Andreas fault (SAF) and the projected position of the Mendocino triple junction (MTJ) through time (arrows). CL=Clear Lake, S= Sonoma, BH= Berkeley Hills, QS= Quien Sabe, P= Pinnacles, and N= Neenach volcanic fields; GGF= Geysers Geothermal Field; and LP= Lassen Peak.

Fig. 2. Current plate geometry in the vicinity of Clear Lake (CL) and the Mendocino triple junction (MTJ). Arrows show the motions of the Gorda (G), Pacific (P), and North American (NA) plates. A "no slab window" is created by net migration of the MTJ to the north.

Fig. 3. Distribution of volcanic rocks and their vents in the Clear Lake region (revised from Hearn et al., 1981). The distributions are shown for four eruptive periods as defined by Donnelly-Nolan et al. (1981). (A) The initial eruptive period (2.1 to 1.3 Ma) is dominated by mafic lavas erupted from a large number of vents spread throughout the region. The northern portion of the Sonoma volcanics is also shown (patterned area). (B) The three succeeding periods of volcanism show a generally migration of volcanism to the north. Episodes 2 and 3 (1.1 to 0.8 and 0.65 to 0.3 Ma) are dominated by silicic volcanic rocks, whereas episode four (0.1 to 0.01 Ma) shows a return to dominantly mafic volcanism.

Fig. 4. Hypothetical cross sections (~E-W) through the magmatic system underlying the Mt. Konocti area at successive stages in its development based on petrologic study (Stimac, 1991). Isotherms are based on geothermometry from lavas and well data. (A) At an early stage, the magmatic system consisted of a single large silicic magma body. This body may have been underlain by intermediate to mafic magmas and cumulates trapped beneath it following addition of mafic magma to the system. (B) At an intermediate stage, a portion of the crystal-poor rhyolitic magma has been erupted. The remaining silicic magma has undergone partial crystallization and cooling. The large single system has segmented into a number of smaller sub-systems. A growing pile of mafic rocks has accumulated at the base of the silicic system, whereas mafic lavas were vented on the periphery and through earlier crystallized portions of the silicic system. (C) At a late stage, dacites where produced by an increased influx of mafic magma into the system, partially assimilating silicic crystal mush zones. The unexposed plutonic complex probably consists of sheet-like to pod-like, normally zoned granitic and granodioritic composite plutons underlain by dioritic to gabbroic rocks.



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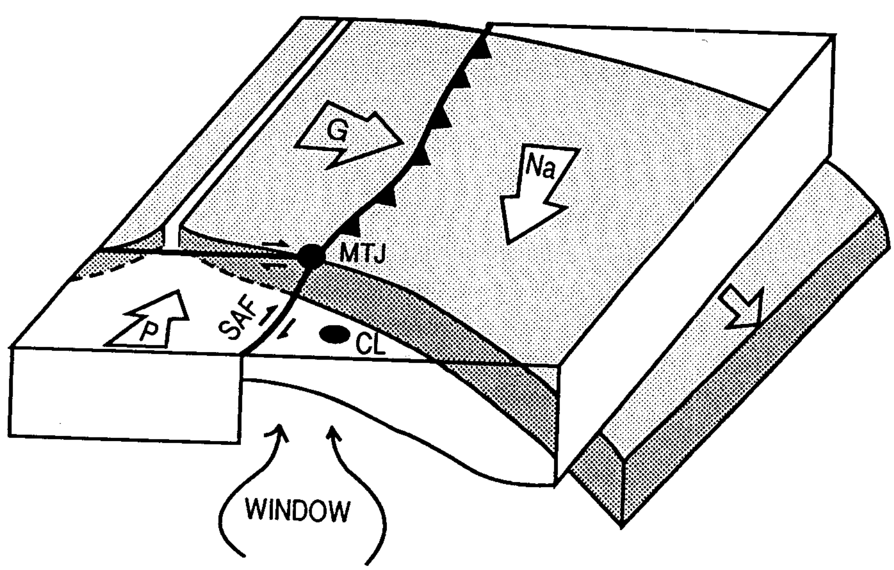

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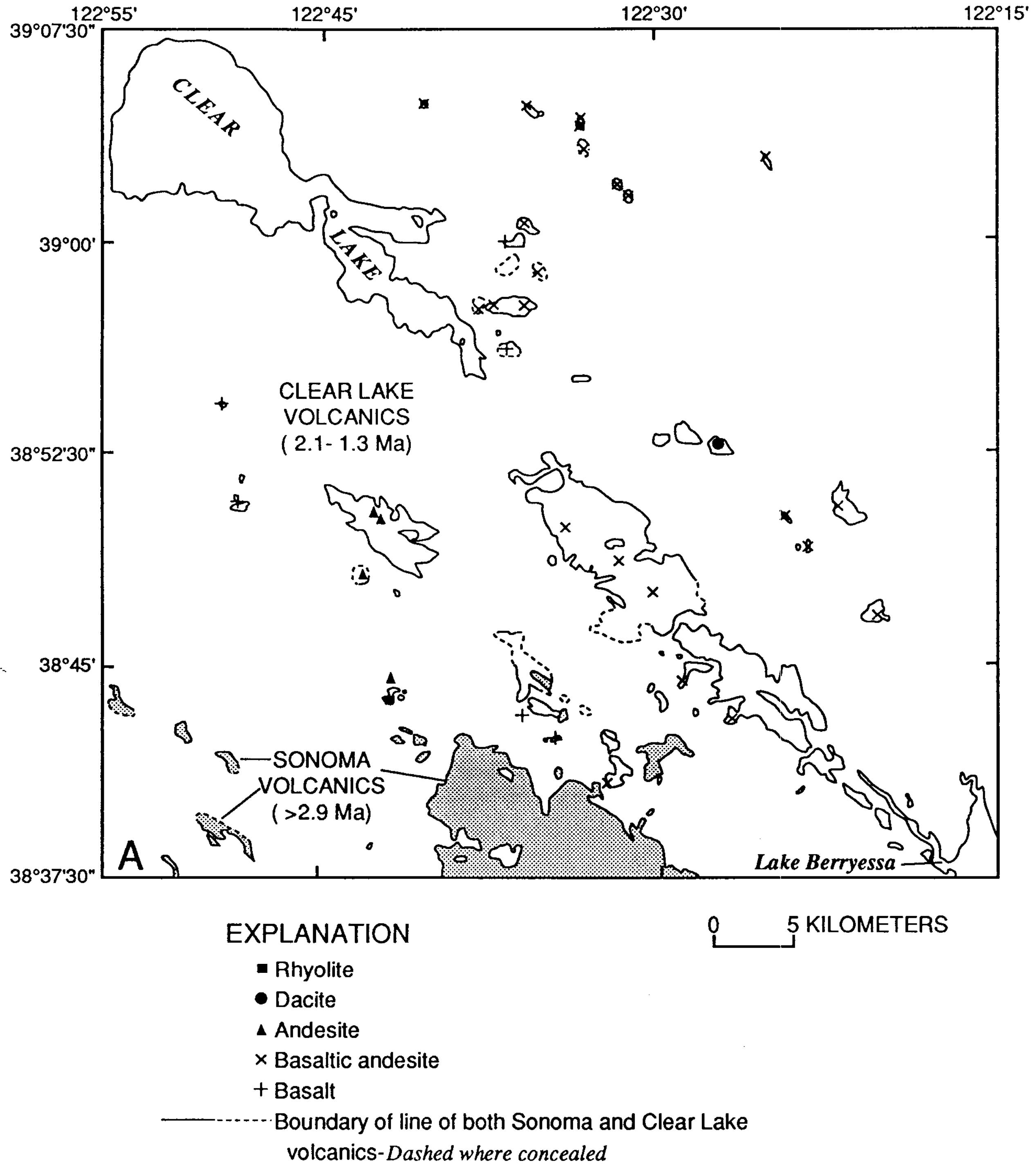

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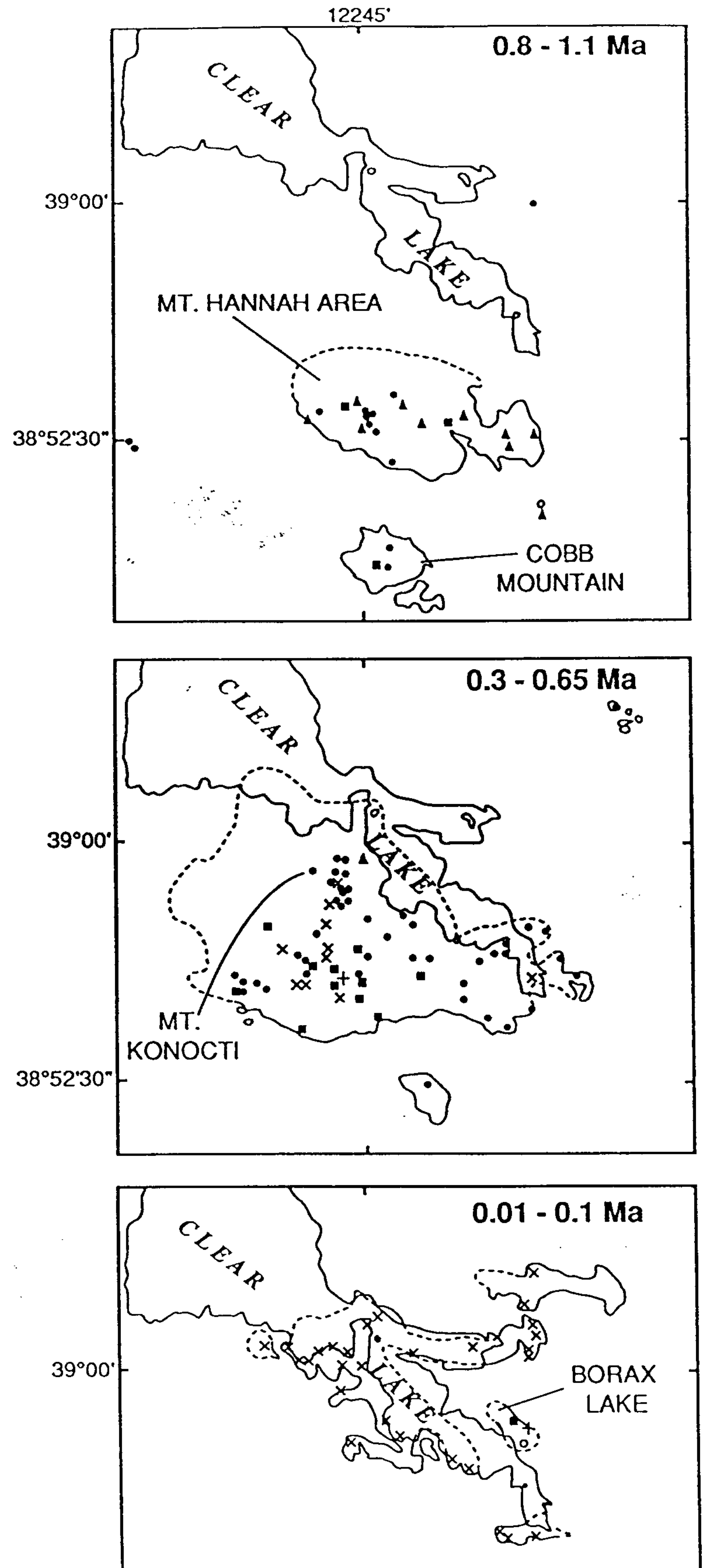


12245'
0.8 - 1.1 Ma
CLEAR
LAKE
39°00'
MT. HANNAH AREA
38°52'30"
COBB
MOUNTAIN
0.3 - 0.65 Ma
CLEAR
LAKE
39°00'
MT.
KONOCTI
38°52'30"
0.01 - 0.1 Ma
CLEAR
LAKE
39°00'
BORAX
LAKE

3 B

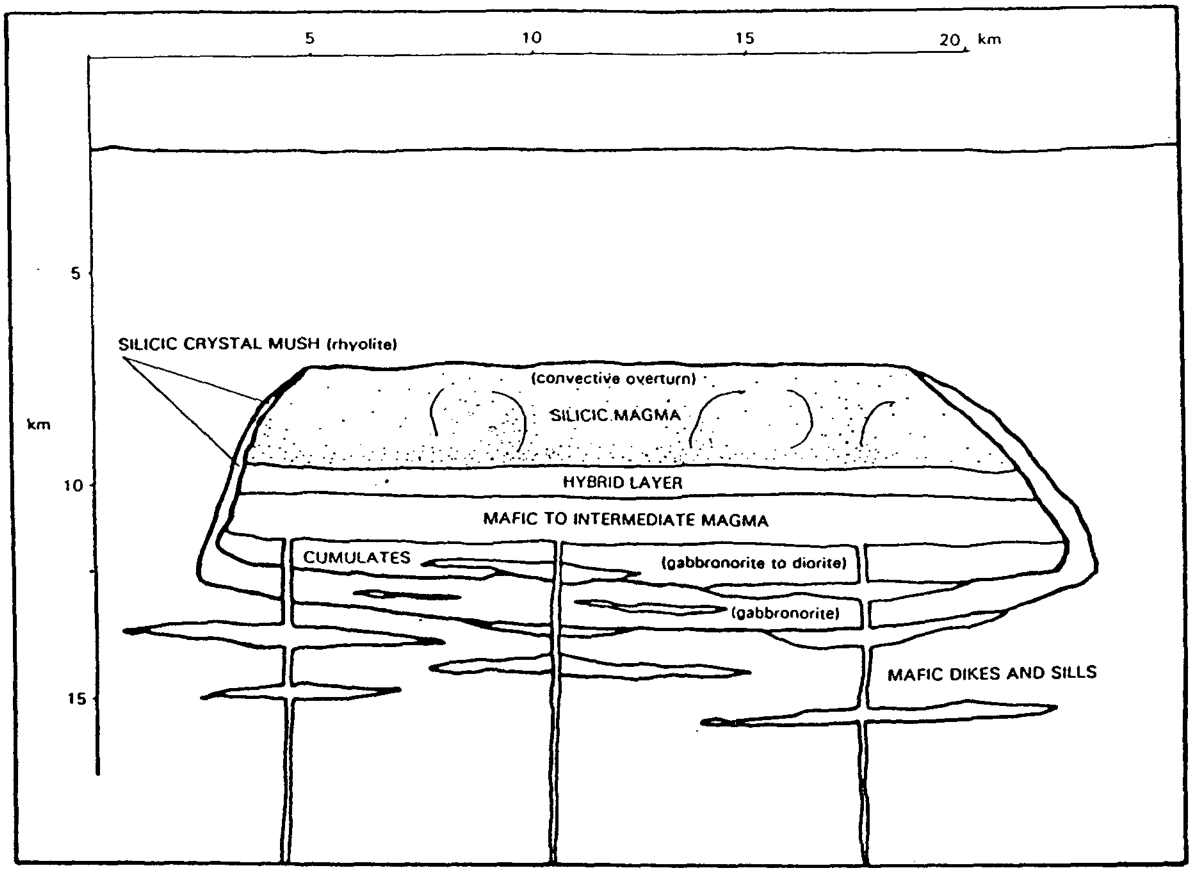
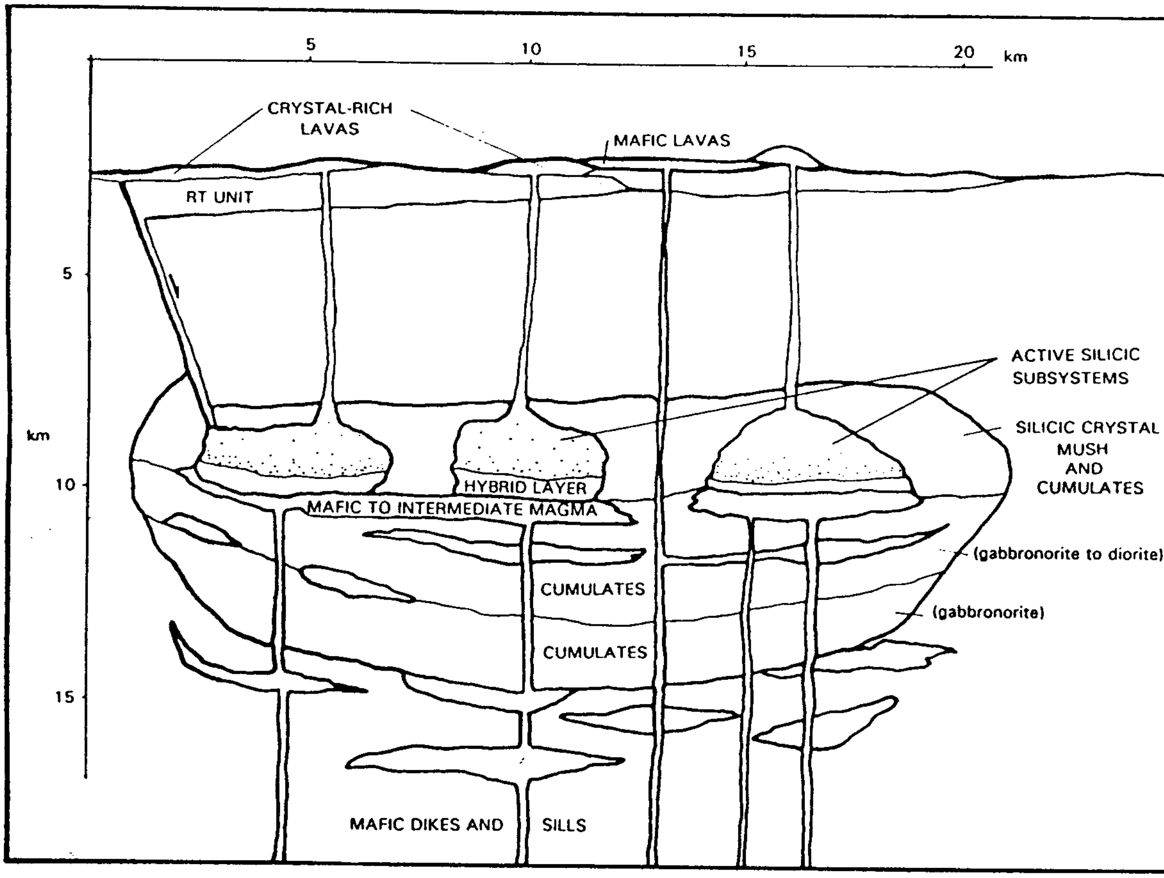
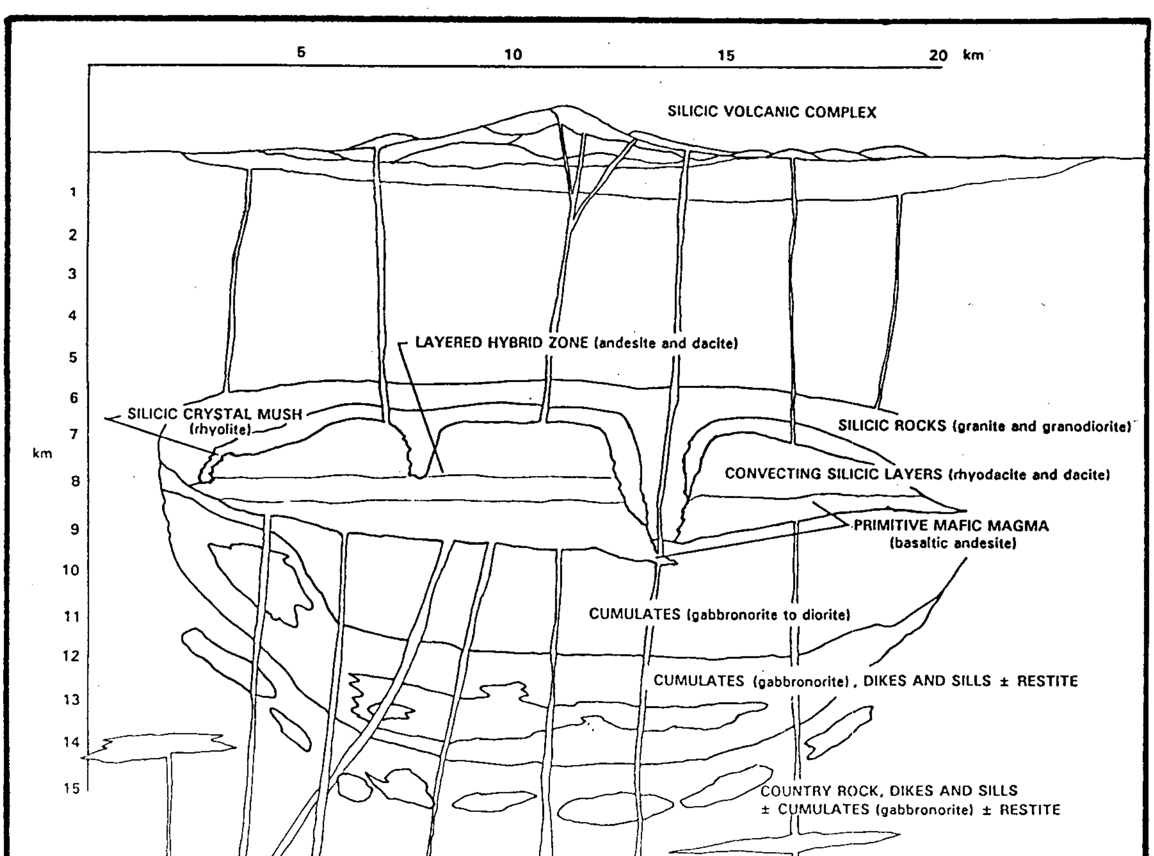


Fig. 4. Hypothetical cross sections through the magmatic system underlying the Mt. Konocti area at successive stages in its development based on petrologic study (Stimac, 1991). (A) At an early stage, the magmatic system consisted of a single large silicic magma body. This body may have been underlain by intermediate to mafic magmas and cumulates trapped beneath it following addition of mafic magma to the system. (B) At an intermediate stage, early crystal-poor rhyolitic magma has been partially erupted. The remaining silicic magma has undergone partial crystallization and cooling. The large single system has segmented into a number of smaller sub-systems. A growing pile of mafic rocks has accumulated at the base of the silicic system, whereas mafic lavas were vented on the periphery and through earlier crystallized portions of the silicic system. (C) At a late stage, dacites where produced by an increased influx of mafic magma into the system, partially assimilating silicic crystal mush zones. If exposed, the plutonic complex would consist of sheet-like to pod-like normally zoned granitic and granodioritic composite plutons underlain by dioritic to gabbroic rocks.



5
10
15
20
km
CRYSTAL-RICH LAVAS
MAFIC LAVAS
RT UNIT
5
ACTIVE SILICIC SUBSYSTEMS
km
SILICIC CRYSTAL MUSH AND CUMULATES
10
HYBRID LAYER
MAFIC TO INTERMEDIATE MAGMA
(gabbronorite to diorite)
CUMULATES
(gabbronorite)
CUMULATES
15
MAFIC DIKES AND SILLS



5
10
15
20 km
SILICIC VOLCANIC COMPLEX
1
2
3
4
5
LAYERED HYBRID ZONE (andesite and dacite)
6
SILICIC CRYSTAL MUSH (rhyolite)
7
SILICIC ROCKS (granite and granodiorite)
km
8
CONVECTING SILICIC LAYERS (rhyodacite and dacite)
9
PRIMITIVE MAFIC MAGMA (basaltic andesite)
10
11
CUMULATES (gabbronorite to diorite)
12
CUMULATES (gabbronorite), DIKES AND SILLS ± RESTITE
13
14
15
COUNTRY ROCK, DIKES AND SILLS ± CUMULATES (gabbronorite) ± RESTITE