PROCEEDINGS, Twenty-second Workshop **on Geothermal Reservoir Engineering**
Stanford University, Stanford, California. January 27-29, 1997
SGP-TR-155

NEW CONSTRAINTS ON THE TIMING OF MAGMATISM, VOLCANISM, AND THE ONSET OF VAPOR-DOMINATED CONDITIONS AT THE GEYSERS STEAM FIELD, CALIFORNIA

Jeffrey B. Hulen[1], Matthew T. Heizler[2], James A. Stimac', Joseph N. Moore', and Jeffrey C. Quick[1]

1. Energy and Geoscience Institute at the University of Utah, Salt Lake City, Utah 84108
2. New Mexico Geochronological Research Laboratory (NMGRL), Socorro, NM 85715
3. Unocal Geothermal and Power Operations, Santa Rosa, CA 95401

ABSTRACT

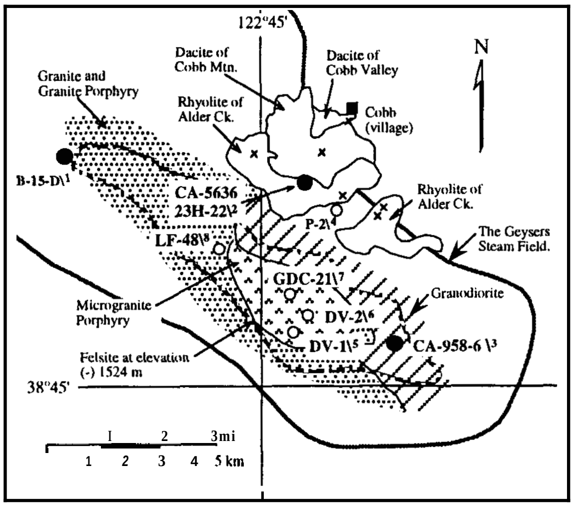
$^{40}Ar/^{39}Ar$ incremental-heating age spectra for two plutonic rocks and a vein adularia from The Geysers steam field, numerically modeled in the light of geologic constraints, indicate that: **(1)** The major granodiorite phase of the "felsite" pluton underlying the steam field, at least in one location, has an absolute age of 1.09 ± 0.04 Ma; it is almost certainly the crystallized magmatic equivalent of a dacite in the overlying Cobb Mountain volcanic center; **(2)** A microgranite porphyry dike, with a minimum age of 1.1 Ma, is permissively a feeder for an older Cobb Mountain unit, the 1.2 Ma rhyolite of Alder Creek; **(3)** The adularia, from Geysers Coring Project corehole SB-15-D, precipitated at 0.57 ± 0.03 Ma in the probable temperature range 300-330°C. The feldspar may have remained near this temperature until 0.28-0.25 Ma, during which interval it rapidly cooled to 260°C, and after which it continued cooling gradually to the modern 230°C.

In conjunction with the adularia's modeled age spectrum, trapping temperatures and pressures of CO_2-rich fluid inclusions in coexisting quartz suggest that The Geysers in this region may already have been vapor-dominated at about 0.26 Ma and 290°C. The rapid temperature drop recorded by the adularia may be linked to the onset of vapor-dominated conditions. Pruess (1985) and Shook (1995) have shown that boiling and large-scale venting of a high-temperature liquid-dominated system like the one which existed once at The Geysers would result in just such a steep temperature decline. We speculate that the caprock on this portion of the hot-water system ruptured catastrophically at about 0.26 Ma during major dislocation along the nearby Big Sulphur Creek strike-slip fault zone. Deeply-penetrating dilational jogs created by the faulting conceptually focused the venting, which in turn permitted the birth of The Geysers steam reservoir.

INTRODUCTION

The Geysers steam reservoir **(Fig. 1)** and its precursor hot-water system are intimately related spatially to the "felsite", an hypabyssal pluton of batholithic dimensions (Schriener and Suemnicht, 1981). Previous attempts to age-date this igneous body have met with mixed success. Schriener and Suemnicht (1981) employed the K-Ar technique to obtain an age range of 2.7-0.9 Ma for cuttings of the felsite, and noted its compositional and temporal affiliation with overlying volcanic rocks of the Pliocene-Holocene Clear Lake volcanic field (Donnelly-Nolan et al., 1981). Using the more precise $^{40}Ar/^{39}Ar$ total-fusion method, Pulka (1991) obtained ages of 1.2-0.95 Ma for a granodiorite in the felsite and 0.57 Ma for an overlying rhyolite porphyry dike **(Fig. 1).** Dalrymple (1992) argued that both the K-Ar and $^{40}Ar/^{39}Ar$ total-fusion techniques were inappropriate for The Geysers because of likely post-emplacement thermal and hydrothermal effects. He utilized instead the $^{40}Ar/^{39}Ar$ incremental-heating method to obtain age ***spectra*** for three cores of the felsite **(Fig. 1).** The spectra revealed what he interpreted to be these rocks' minimum ages, in the range 0.6 to 1.4 Ma.

Guided by results of these investigations, we have obtained new $^{40}Ar/^{39}Ar$ age spectra for two samples of The Geysers felsite -- the granodiorite core (from well CA-958-6) previously dated by Pulka (1991); and a microgranite porphyry penetrated by Santa Fe geothermal well CA-5636-23H-22 **(Fig. 1).** We have also age-dated, by the same method, a vein adularia from Geysers Coring Project corehole SB-15-D.



Well locations at sample depth
- ● New $^{40}Ar/^{39}Ar$ age dates (this study)
- O Previously dated plutonic rocks or adularia

× Previously dated volcanic rocks (please refer to text)

1/ Adularia
2/ Microgranite porphry (orthoclase)
3/ Granodiorite (orthoclase and biotite); also Pulka. 1991 (orthoclase)
4/ Rhyolite porphry (orthoclase); Pulka, 1991
5/ Adularia; McLaughlin et al., 1983
6/ Microgranite porphyry (orthoclase and adularia); Dalrymple, 1992
7/ Granite (orthoclase); Dalrymple, 1992
8/ Granite (orthoclase); Dalrymple. 1992

‘igure1. Location map, also showing distribution of ıajor rock types at the top of The Geysers felsite.

ieologically constrained thermal models of the age pectrum of this feldspar provide important clues to ıe timing of formation of The Geysers vapor-domiated geothermal regime.

.s the world's largest known high-temperature geoıermal system, The Geysers has been meticulously escribed by numerous geoscientists and reservoir ngineers for nearly forty years. The collected papers ı Stone (1992) and McLaughlin and Donnelly-Nolan 1981) provide a comprehensive overview of the :eam field and its geologic setting. The reader is also eferred to White et al. (1971), Pruess (1985), Moore nd Gunderson (1995), and Shook (1995) as freuently cited accounts of The Geysers' origin and volution. The petrogenesis of portions of the associted Clear Lake volcanic field is detailed by Stimac 1991), Stimac and Pearce (1992), and Stimac and Vark (1992).

GEOLOGIC SETTING

The Geysers granodiorite -- This is one of three major plutonic rock types comprising the felsite. It is exposed at the top of the composite pluton only in the southeastern part of the field **(Fig. 1)**, but underlies the other two principal igneous phases -- granite and microgranite porphyry -- in most deeper felsite-penetrating wells (Hulen and Nielson, 1993, 1996). It is a fine-grained, subhedral- to euhedral-granular, seriate to incipiently porphyritic rock with "phenocrysts" of orthopyroxene, biotite, orthoclase, and oscillatory-zoned plagioclase embedded in a just slightly finer-grained groundmass. The groundmass consists of plagioclase, biotite, hornblende, orthopyroxene, and rare clinopyroxene with interstitial to poikilitic-textured quartz and orthoclase.

The CA-958-6 granodiorite core sample selected for age-dating **(Fig. 1)** is, for the felsite, remarkably fresh. Some of the orthopyroxene is deuterically altered to hornblende, which, along with the pyroxene, is altered partially to deuteric biotite. Apart from a few quartz-epidote-chlorite veinlets, however, hydrothermal effects are confined to slight local chloritization of the magmatic and deuteric mafic phases.

Microgranite Porphyry -- The microgranite porphyry penetrated by well CA-5636-23H-22 **(Fig. 1)** is from an apparent dike at least 2 km above the main mass of the felsite (Unocal et al., 1992). This dike rock is nearly identical texturally and mineralogically to its counterpart deep in that large igneous body. In both cases, the porphyry consists of quartz, oligoclase and orthoclase phenocrysts embedded in a micrographic to microgranophyric groundmass. Biotite, the principal mafic mineral, is mostly chloritized; a few associated subequant chlorite clots may be altered pyroxene phenocrysts. The dike is moderately silicified and adularized as well as sparsely altered to chlorite, prehnite, epidote, tourmaline, and pyrite.

Vein Adularia -- The age-dated adularia is from a steeply-dipping hydrothermal vein cutting Franciscan metagraywacke at a depth of 471.8 m in corehole SB-15-D **(Fig. 1).** In addition to the feldspar, the vein contains principally quartz and calcite, with minor epidote, chlorite, pyrite, chalcopyrite, and traces of acicular actinolite. Cross-cutting and infilling textures of these phases indicate that actinolite was the earliest mineral precipitated, followed in sequence by epidote, quartz-adularia-calcite, calcite, and latest-stage quartz. Adularia is also common as an alteration product of clastic plagioclase immediately adjacent to this and similar veins in the SB-15-D core.

^{40}Ar/^{39}Ar AGE-DATING

General -- The ^{40}Ar/^{39}Ar age-dating method has several distinct advantages over conventional K-Ar techniques (Dalrymple et al., 1981; McDougall and Harrison, 1988). For one thing, the sample does not require total fusion for analysis, but rather can be incrementally heated. The 40Ar/39Ar ratio can be measured for each heating increment and fraction of argon released, and this allows for the generation of age spectra. For potassium feldspars, the spectra can be numerically modeled, taking into account not only independent paleotemperature data, but also argon-closure temperatures for different diffusion domains entrapping the gas (Lovera et al., 1993; Fitz Gerald and Harrison, 1993). The models yield hypothetical, non-unique thermal histories, the more likely of which can be selected according to how closely they match the age spectrum and satisfy local geologic conditions.

Space limitations for this volume preclude full tabulation of supporting ^{40}Ar/^{39}Ar analytical data and a detailed account of the methods and procedures employed to obtain this information. The data are available upon request from the authors. For more information on geochronology, thermochronology, and the ^{40}Ar/^{39}Ar method in general, please refer to Dalrymple et al.(1981), Heizler and Harrison (1988), and McDougall and Harrison (1988).

Results -- Age spectra for the two Geysers plutonic rocks are shown as Figure 2. For the granodiorite, primary biotite and orthoclase were analyzed. The biotite produced a very simple age spectrum, and a "plateau" age (generally defined if three or more contiguous heating steps, comprising at least 50% of the ^{39}Ar released, agree within error limits) of 1.09 +- 0.04 Ma **(Fig. 2A, top).** The orthoclase age spectrum shows a gradient with a real lower limit of about 0.7 Ma and a "terminal age" (corresponding to the highest-temperature heating increments) which is equivalent to the 1.1 Ma biotite age **(Fig. 2A, bottom).** As is typical, apparent ages for the initial 5-10% of this orthoclase age spectrum have large uncertainties. These ages are not believed to be geologically relevant (e.g. Dalrymple, 1992). Because the age spectrum for the biotite from the granodiorite is essentially undisturbed; because the disturbed orthoclase spectrum has virtually the same terminal age as the biotite; and because of the unaltered character of this core, we feel confident that the granodiorite crystallized at very close to 1.09 Ma.

The age spectrum for orthoclase from the microgranite porphyry dike shows a gradient ranging from about 0.7 to 1.1 Ma **(Fig. 2B)** which is very similar to its counterpart from the granodiorite. The porphyry is hydrothermally altered, so the upper limit of its orthoclase age spectrum is the rock's minimum age.

The SB-15-D adularia age spectrum is also a gradient, increasing from about 0.35 Ma to about 0.6 Ma **(Fig. 3).** The spectrum's oldest apparent ages, averaging 0.57 ± 0.03 Ma, correspond to a calculated argon-closure temperature of about 375°C. This is higher than

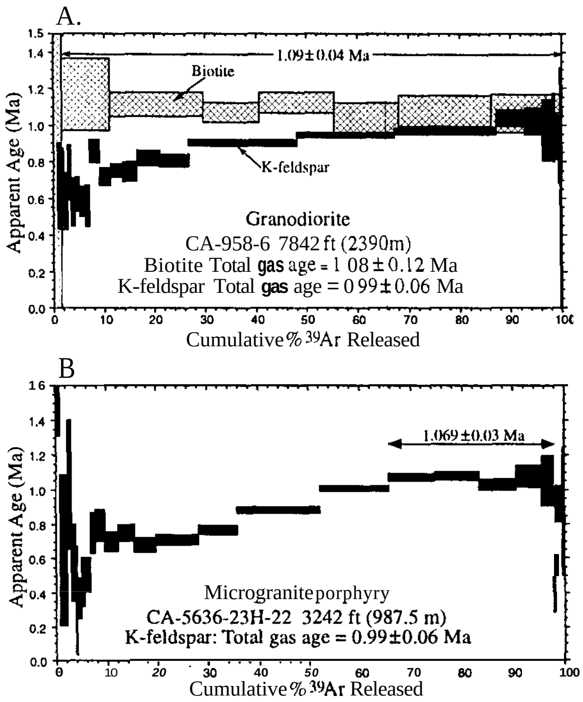


Figure 2. ^{40}Ar/^{39}Ar incremental-heating age spectra for two samples of The Geysers felsite. A -- Biotite and orthoclase age spectra for granodiorite from Calpine Corporation well CA-958-6, depth 2390 m. B -- Orthoclase age spectrum for microgranite porphyry from Santa Fe Geothermal well CA-5636-23H-22, depth 987.5 m.

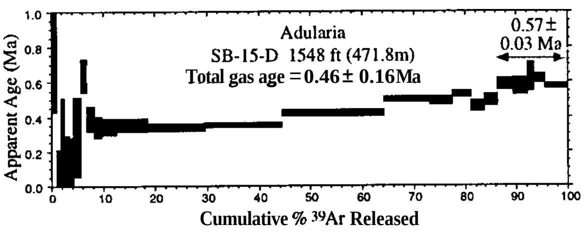


Figure **3.** ^{40}Ar/^{39}Ar incremental-heating age spectrum for vein adularia from Geysers Coring Project corehole SB-15-D, depth 471.8 m.

the maximum possible temperature experienced by the vein's host rock (see "vitrinite reflectance", below). Therefore, the corresponding 0.57 Ma age is not only a minimum, but a likely true age of precipitation. Another vein adularia inferred from published accounts to be from Unocal well DV-I (Fig. **1)** was previously dated by **K-Ar** methods at 0.69 ± 0.03 Ma (Moore, 1980; McLaughlin et al., 1983). Because of the analytical technique, this is the feldspar's minimum age.

THE FELSITE AND THE COBB MOUNTAIN VOLCANIC CENTER

The felsite is an obvious candidate as the plutonic equivalent of the overlying Cobb Mountain volcanic center **(Fig. 1)** in the Clear Lake volcanic field. Not only are the major units of each body silicic, they all contain orthopyroxene and biotite as the principal mafic phases. Hulen and Nielson (1993, 1996) used geochemical evidence to suggest that the granodiorite and dacite might be plutonic-volcanic counterparts. This suggestion is strongly supported by the granodiorite's 1.09 Ma crystallization age.

However, there are two dacites on the mountain which permissively could be the granodiorite's volcanic equivalent -- the dacite of Cobb Mountain (1.05-1.06 ± 0.02 Ma) and the dacite of Cobb Valley (1.06-1.10 ± 0.02 Ma) (Donnelly-Nolan et al., 1981) (Fig. **1).** The former contains phenocrysts of plagioclase, sanidine, quartz, biotite, orthopyroxene, and clinopyroxene in a glassy to devitrified cryptocrystalline groundmass. Hornblende is locally present in glomerocrysts with plagioclase, quartz, and orthopyroxene. This dacite also contains quenched andesitic inclusions. The dacite of Cobb Valley is slightly less silicic in composition than the dacite of Cobb Mountain. Phenocrysts in the former are principally orthopyroxene, clinopyroxene, and plagioclase, with very rare sanidine and quartz; there are apparently no andesitic inclusions. The phenocryst mineralogy and overall chemical composition of these rocks lead us to conclude that the more likely volcanic counterpart of the granodiorite is the dacite of Cobb Mountain.

The 21.1 Ma microgranite porphyry dike is a possible ancient feeder for the rhyolite of Alder Creek (1.2 Ma; Turrin et al., 1994)(**Fig. 1).** However, although the two rocks are similar in composition, in the absence of a true crystallization age for the porphyry, its genetic affiliation with the rhyolite remains speculative.

AGE OF INCEPTION OF VAPOR-DOMINATED CONDITIONS

Geologic Constraints -- The age spectrum for the SB-15-D adularia can be used to help fix the time at which The Geysers became vapor-dominated. A variety of numerical thermal-history models duplicate approximately the observed spectrum, but few are geologically realistic. Observations and measurements used in selecting the more likely scenarios are as follows:

Adularia argon-closure temperatures -- The SB-15-D adularia has two principal calculated argon-closure temperatures, one as noted at about 375°C; the other at about 320°C. These closure temperatures provide critical limits for the associated thermal histories.

Fluid Inclusions -- Fluid inclusions in quartz associated with the SB-15-D adularia were studied to determine the temperatures and compositions of the fluids responsible for mineralization. The inclusions are variously of primary and secondary origin; are two-phase (liquid plus vapor); and are either liquid- or vapor-rich. The primary inclusions record conditions at the time the host crystal was precipitating.

Fourier Transform Infrared Spectroscopy (FTIR) of certain primary vapor-rich inclusions in the quartz indicates that they are filled mostly with C02 (R. Aines and J. Moore, unpublished data). Heating and freezing measurements on associated primary liquid-rich inclusions yield homogenization temperatures averaging close to 290°C and an apparent salinity of 0.35 wt% NaCl equivalent.

The coexistence of liquid- and vapor-rich fluid inclusions indicates that the mineralizing hydrothermal fluids were boiling at the time the inclusions were trapped in the growing quartz crystal. The distinctive nature of the CO_2-rich inclusions suggests that the boiling occurred under vapor-dominated conditions.

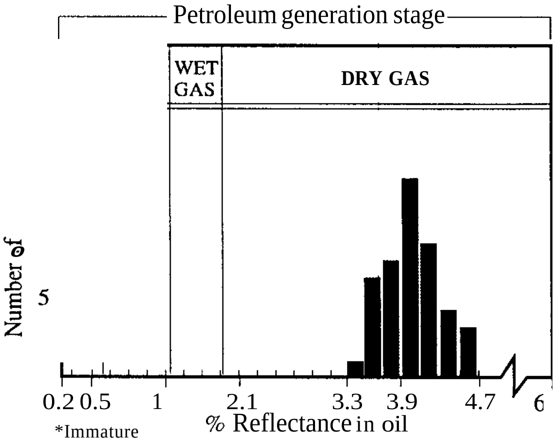
Moore and Gunderson (1995) showed that low-salinity inclusions like those in the SB-15-D vein most likely represent steam condensate derived by boiling of an indigenous, more saline, connate-metamorphic fluid. FTIR of the SB-15-D CO_2-rich inclusions reveals almost no associated water. Therefore these inclusions did not simply trap steam. The CO_2, when supercooled on the fluid-inclusion stage, nucleates as a pure solid phase which sublimates upon reheating. This behavior, along with the calculated depth of mineralization (see Moore and Gunderson, 1995), indicates that at the time of inclusion entrapment, fluid pressures were subhydrostatic. Based on these relationships, we believe it likely that the vapor-rich inclusions trapped CO_2 in a low-pressure gas cap at the top of the evolving vapor-dominated system.

From the foregoing, it appears that when the temperature of the hydrothermal system was about 290°C (60°C hotter than now) at this site and elevation, vapor-dominated conditions already prevailed.

Vitrinite Reflectance -- The metagraywacke host rock for the 471.8 m adularia-bearing vein contains abundant vitrinite. The reflectance of this organic matter increases irreversibly with increasing temperature, providing an effective maximum geothermometer. For this study, we applied an empirical vitrinite-reflectance geothermometer calibrated by Barker and Pawlewicz (1994).

Vitrinite near the adularia-bearing vein has a mean random reflectance of 4.02% **(Fig. 4).** This corresponds to a peak paleotemperature of 330 ± 20°C (Barker and Pawlewicz, 1994). The upper limit is geologically unreasonable, since the SB-15-D rocks lack the diagnostic hydrothermal or metamorphic minerals (for example, clinopyroxene, garnet, and biotite) which would almost certainly form at such high temperatures. On the other hand, actinolite is present in the vein, indicating a formation temperature of at least 290°C. This corresponds closely to trapping temperatures for primary liquid-rich inclusions in associated vein quartz.

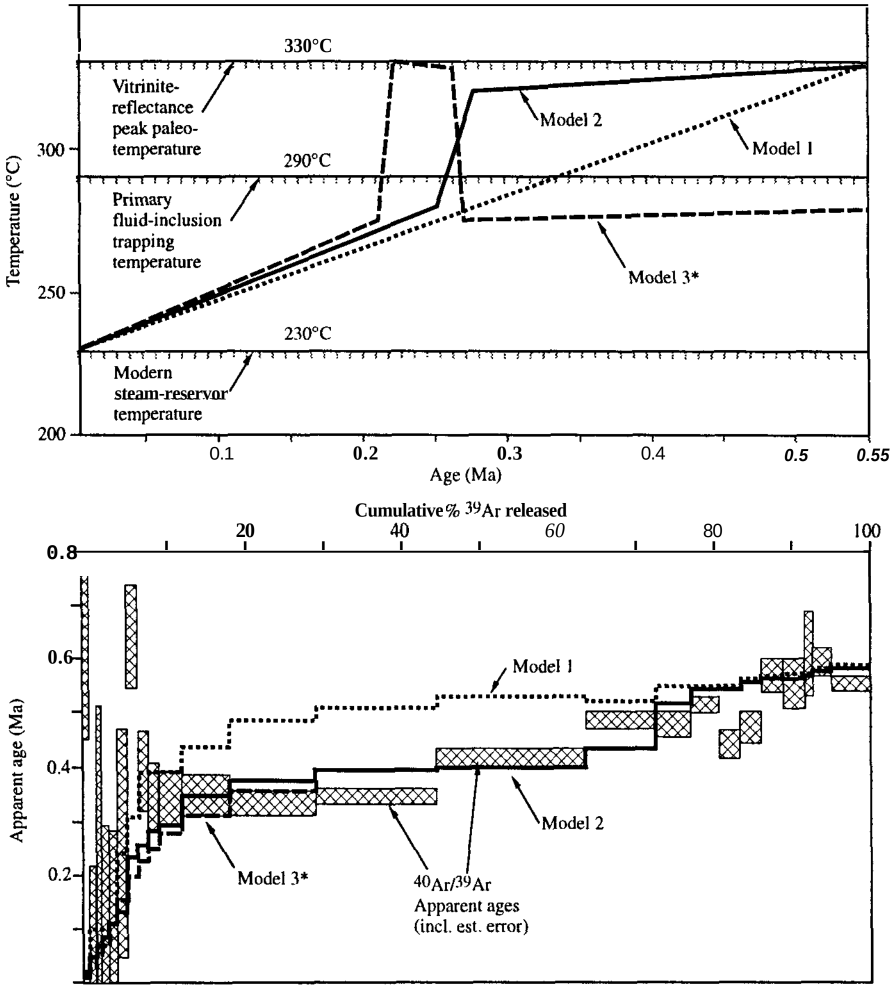
We believe it improbable that this rock attained its peak paleotemperature only after vein mineralization had ceased. At this elevation in The Geysers (more than a kilometer above the felsite; Unocal et al., 1992), such high temperatures would have required convective heat transfer from the pluton. The implied, early, high-temperature fluids almost certainly would have recorded their passage through the future SB-15-D rocks in the form of hydrothermal veins. Provisionally, therefore, we will accept the 330°C vitrinite-reflectance peak paleotemperature as having been "locked in" at the time the adularia precipitated.



mean random reflectance of vitrinite **= 4.02%**
number of counts **= 41**
standard deviation **= 0.28**

Figure 4. Histogram showing distribution of vitrinite-reflectance values for argillaceous metagraywacke from a depth of 471.5 m in Geysers Coring Project corehole SB-15-D. The mean random reflectance of this vitrinite population corresponds to a peak paleotemperature of 330 ± 20°C according to the empirical vitrinite-reflectance geothermometer of Barker and Pawlewicz (1994).

Thermal-History Modeling -- Three numerical thermal-history simulations of the SB-15-D adularia age spectrum are shown on **Figure 5.** The simulations take into account the geologic information presented above, as well as the reported modern steam-reservoir temperature of 230°C. Model 1 commences at the interpreted thermal maximum of 330°C, and invokes steady cooling to the current temperature; it produces an age spectrum about 200,000 yr too old for the



* Yields age spectrum nearly identical to that produced by model 2

Figure 5. Three alternative thermal histories (top) and corresponding age spectra relative to the measured age spectrum (bottom) for adularia from a depth of 471.8 m in Geysers Coring Project corehole SB-15-D. Although models 2 and 3 both match closely the measured spectrum, model 2 is believed to be the more geologically realistic (please refer to text for explanation). Inception of the models at 0.55 Ma rather than the precipitation age of 0.57 Ma is an artifact in the modeling program which does not affect the subsequent cooling history.

intermediate-temperature heating steps. Models 2 and 3, however, closely match the actual spectrum.

Model 2, also beginning with the interpreted thermal maximum, requires maintenance of the temperature at very close to this value until about 0.28 Ma. At this point the temperature begins to drop rapidly, cooling to 260°C within 25,000 yr. Over the next 250,000 yr, the feldspar continues cooling, but much more gradually, to the modern reservoir temperature.

Model 3 begins at an arbitrarily lower temperature, 280°C, then near-isothermally cools to 275°C by 0.28 Ma, when a major thermal "spike" is initiated **(Fig. 5).** This spike conceptually could be due to a small shallow igneous intrusion or rapid upflow of hot waters from greater depths. The spike would peak at the paleotemperature maximum, where it would hold nearly steady for 40,000 yr. A rapid drop in temperature then would ensue, terminating by 0.21 Ma. Subsequent gradual cooling would diminish the temperature to the current 230°C.

At this stage of our investigation, we strongly favor model 2 over model 3 as portraying the more likely thermal history of the SB-15-D adularia. There is no direct evidence for the temperature spike of model 3.

Fluid-inclusion systematics show that in this portion of The Geysers, subhydrostatic pressures prevailed when the hydrothermal system had reached a temperature of 290°C. According to the preferred model, this temperature was attained between 0.28 and 0.25 Ma, probably at about 0.26 Ma **(Fig. 5).** The clear implication is that at this site and elevation, The Geysers became vapor-dominated over a quarter of a million years ago.

DISCUSSION AND CONCLUSIONS

The new $^{40}Ar/^{39}Ar$ age spectra support a long-suspected intrusive-extrusive relationship at The Geysers while furnishing new insight into the evolution of the associated magmatic-hydrothermal system. At least one portion of The Geysers granodiorite has now been confirmed as the likely plutonic equivalent of one of two overlying dacites -- probably the 1.1 Ma dacite of Cobb Mountain. The hydrothermal system associated with these igneous rocks precipitated vein adularia in the future SB-15-D core at about 0.57 Ma. The system apparently remained liquid-dominated until sometime between 0.28 and 0.25 Ma, and has likely since been vapor-dominated. We caution that the model used to arrive at this conclusion requires refinement, since in part it would seem at odds with established knowledge of hydrothermal systems. For example, maintenance of the initial high temperature nearly unchanged for such a long time (290,000 yr) might prove to be geologically unrealistic. However, in spite of remaining uncertainties, the model probably cannot be drastically modified and still match the observed age spectrum.

If we accept model 2 **(Fig. 5)** as the preferred thermal history, its steep temperature drop between 0.28 and 0.25 Ma could be linked to the onset of vapor-dominated conditions. Pruess (1985) and Shook (1995) show that such precipitous cooling will accompany the boiling and rapid venting required to establish a vapor-dominated regime. We speculate that such venting may have occurred through major vertical conduits --“pipes”-- developed along the northwest-trending Big Sulphur Creek strike-slip fault zone just southwest of the SB-15-D site. Deeply-penetrating dilational jogs created along this fault zone could have ruptured the hydrothermal system’s caprock, triggering the boiling and venting which led to inception of this part of the steam reservior.

ACKNOWLEDGEMENTS

This research was supported by the **U.S.** Department of Energy, Geothermal Division (Marshall Reed, Program Manager), under contract DE-AC07-95ID13274. Said support does not constitute an endorsement of the views expressed in the paper. The felsite samples which made much of the study possible were provided by Calpine Corporation and Santa Fe Geothermal. Discussions with Phillip M. Wright helped us evaluate the relative merits of alternative thermal-history models. Special thanks to Ron Wilson for his extraordinary efforts in timely production of the illustrations shown at the Workshop and reproduced in this document.

REFERENCES

Barker, C.E., and Pawlewicz, M.J., 1994, Calculation of vitrinite reflectance from thermal histories and peak temperatures -- A comparison of methods *in* Vitrinite reflectance as **a** maturity parameter: Applications and limitations (P.K. Mukhopadhyay and W.G. Dow, editors): American Chemical Society, Symposium Series, No. 570, p. 216-229.

Dalrymple, G.B., Alexander, E.C., Jr., Lanphere, M.A., and Kraker, G.P., 1981, Irradiation of samples for $^{40}Ar/^{39}Ar$ dating using the Geological Survey TRIGA reactor: **U.S.** Geological Survey, Professional Paper 1176, 73 p.

Dalrymple, G.B., 1992, Preliminary report on $^{40}Ar/^{39}$ incremental-heating experiments on feldspar samples from the felsite unit, Geysers geothermal field, California: U.S. Geological Survey, Open-File Report 92-407, 15 p.

Donnelly-Nolan, J.M., Hearn, B.C., Jr., Curtis, H., and Drake, R.E., 1981, Geochronology and evolution of the Clear Lake Volcanics *in* Research in the Geysers-Clear Lake geothermal area, northern California (R.J. McLaughlin and J.M. Donnelly-Nolan, editors): U.S. Geological Survey, Professional Paper 1141, p. 47-60.

Fitz Gerald, J.D., and Harrison, T.M., 1993, Argon-diffusion domains in K-feldspar I -- Microstructures in MH-10: Contributions to Mineralogy and Petrology. **v.** 113, p. 367-380.

Heizler, M.T., and Harrison, T.M., 1988, Multiple trapped argon-isotope components revealed by $^{40}Ar/^{39}Ar$ isochron analysis: Geochimica et Cosmochimica Acta, v. 54, p. 1295-1303.

Hulen, J.B., and Nielson, D.L., 1993, Interim report on geology of The Geysers felsite, northwestern California: Geothermal Resources Council, Transactions, v. 17, p. 249-258.

Hulen, J.B., and Nielson, D.L., 1996, The Geysers felsite: Geothermal Resources Council, Transactions, v. 20, p. 295-306.

Lovera, O.M., Heizler, M.T., and Harrison. T.M., 1993, Argon-diffusion domains in K-feldspar II -- Kinetic properties of MH-IO: Contributions to Mineralogy and Petrology, v. 113, p. 381-393.

McDougall, I., and Harrison, T.M., 1988, Geochronology and thermochronology by the $^{40}Ar/^{39}Ar$ method: Oxford University Press, 322 p.

McLaughlin, R.J., and Donnelly-Nolan, J.M. (Editors), 1981, Research in the Geysers-Clear Lake geothermal area, northern California: U.S. Geological Survey, Professional Paper 1141, 259 p.

McLaughlin, R.J., Moore, D.M., Sorg, D.H., and McKee, E.H., 1983, Multiple episodes of hydrothermal circulation, thermal metamorphism, and magma injection beneath The Geysers steam field, California (abstract): Geological Society of America, Abstracts with Programs, v. 15, p. 417.

Moore, D., 1980, Hydrothermal alteration minerals of The Geysers steam field, California, and their potential use in exploration: Stanford University, 6th Workshop on Geothermal Reservoir Engineering, Proceedings, 6 p.

Moore, J.N., and Gunderson, R.P., 1995, Fluid-inclusion and oxygen-isotopic systematics of an evolving magmatic-hydrothermal system -- The Geysers, California: Geochimica et Cosmochimica Acta, v. 59, p. 3887-3907.

Pruess, K., 1985, A quantitative model of vapor-dominated geothermal reservoirs as heat pipes in fractured porous rock: Geothermal Resources Council, Transactions, v. 9, pt. II, p. 353-361.

Pulka, F.S., 1991, Subsurface geology at Ford Flat, Geysers geothermal field, northern California: Houghton, Michigan Tech. University, M.S. Thesis, 324 p.

Schriener, A., Jr., and Suemnicht, G.A., 1981, Subsurface intrusive rocks at The Geysers geothermal area, California *in* Proceedings of the symposium on mineral deposits of the Pacific Northwest (M.L. Silberman and C. Field, editors): U.S. Geological Survey, Open-File Report 81-355, p. 295-302.

Shook, M., 1995, Development of a vapor-dominated reservoir with a “high-temperature’’ component: Geothermics, v. 24, p. 489-505.

Stimac, J.A., 1991, Evolution of the silicic magmatic system at Clear Lake, California, from 0.6 to 0.3 Ma: Kingston, Canada, Queens University, Ph.D. Dissertation, 399 p.

Stimac, J.A., and Pearce, T.H., 1992, Textural evidence for mafic-felsic magma interaction in dacitic lavas, Clear Lake ,California: American Mineralogist, v. 77, p. 795-809.

Stimac, J.A., and Wark, D.A., 1992, Plagioclase mantles on sanidine in silicic lavas, Clear Lake, California -- Implications for the origin of Rapakivi texture: Geological Society of America Bulletin, v. 104, p. 728-744.

Stone, C. (Editor), 1992, Monograph on The Geysers geothermal field: Geothermal Resources Council, Special Report 17, 327 p.

Tumn, B.D., Donnelly-Nolan, J.M., and Hearn, B.C., Jr., 1994, $^{40}Ar/^{39}Ar$ ages from the rhyolite of Alder Creek, California -- Age of the Cobb Mountain normal-polarity subchron revisited: Geology, v. 22, p. 251-254.

Unocal Corporation, Geysers Geothermal Company, NCPA, GEO Operator Corporation, Santa Fe Geothermal, and California Department of Water Resources, 1992, Top-of-reservoir and top-of-felsite maps *in* Monograph on The Geysers geothermal field (C. Stone, editor): Geothermal Resources Council, Special Report 17, 327 p. (pocketed maps).

White, D.E., Muffler, L.J.P., and Truesdell, A.H., 1971, Vapor-dominated hydrothermal systems compared with hot-water systems: Economic Geology, v. 66, p. 75-97.