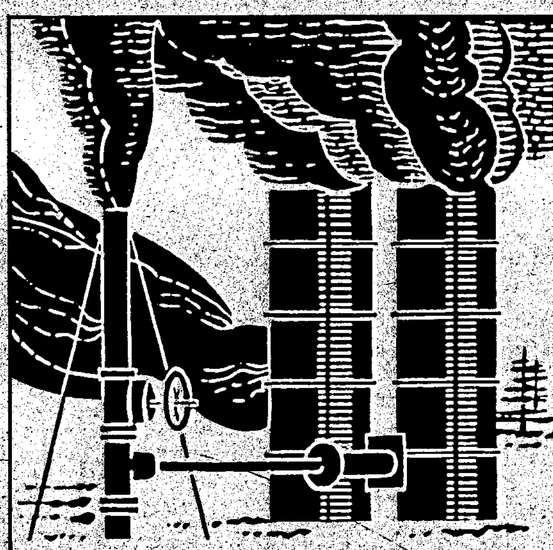
proceedings of THE 17th NEW ZEALAND GEOTHERMAL WORKSHOP 1995



compiled and edited by

M. P. Hochstein, J. Brotheridge and S.F. Simmons

presented by
Geothermal Institute
The University of Auckland
in conjunction with
The Centre for Continuing Education

DISCLAIMER

EVOLUTION OF THE GEYSERS (US) - DATA FROM FLUID-INCLUSION MICROTHERMOMETRY AND GAS GEOCHEMISTRY

J.N. MOORE[1], J.B. HULEN[1] AND D.I. NORMAN[3]

[1] Earth Sciences and Resource Institute, Salt Lake City, Utah, USA
[2] New Mexico Tech, Dept. of Geoscience, Socorro, New Mexico, USA

SUMMARY - The Geysers, California, is the site of an active hydrothermal system that initially developed between about 1.5 and 2 Ma in response to intrusion of a hypabyssal granitic pluton. Mineralogic and fluid-inclusion data demonstrate that the present vapor-dominated regime evolved from an earlier and more extensive, liquid-dominated hydrothermal system. Circulation of these early fluids produced veins characterized by tourmaline and/or biotite ± actinolite ± clinopyroxene within the pluton and adjacent biotite-rich hornfels, actinolite ± ferroaxinite ± epidote, and epidote ± chlorite ± wairakite within the intermediate parts of the thermal system, and calcite in the outer parts. Potassium feldspar and quartz are present in all assemblages. Maximum pressure-corrected homogenization temperatures and apparent salinities of fluid-inclusions in these veins range from 440°C and 44 weight percent NaCl equivalent within the hornfels (<600 m from the pluton) to 325°C and 5 weight percent NaCl equivalent at approximately 1500 m from the intrusion. We suggest that the shallow, moderate-salinity fluids are crustal waters modified by water-rock interactions and that the high-salinity fluids are magmatic brines. The formation of vapor-dominated conditions is reflected in the abrupt appearance of low salinity (0.0 to 0.4 weight percent NaCl equivalent) fluid inclusions with homogenization temperatures near 265°C. These inclusion fluids are thought to represent steam condensate formed as the liquid-dominated system boiled off.

1. INTRODUCTION

The Geysers of northern California is a large, vapor-dominated geothermal resource that covers nearly 150 sq km, within a much larger thermal anomaly (Walters and Combs, 1989). The field produces approximately 1200 MW of electricity from a thick sequence of altered Mesozoic metasediments and an underlying felsic intrusive complex (Schriener and Suemnicht, 1981; Thompson, 1989) that appears to be directly related to the present geothermal activity. In this paper we describe the evolution of the geothermal resource from its initial development as a liquid dominated hydrothermal system to the formation of the present vapor-dominated regime.

2. GEOLOGIC SETTING

The Geysers is located in the Mayacmas Mountains, 150 km north of San Francisco (Fig. 1). This structurally complex range is dominated by oceanic rocks of Jurassic to Cretaceous age that have been assigned to three major rock sequences (McLaughlin, 1981; McLaughlin and Ohlin, 1984). The Franciscan Assemblage, which hosts the bulk of the steam at The Geysers, is structurally the lowest of these three sequences. Within the Mayacmas Mountains, this unit consists mainly of metagraywacke with lesser amounts of argillite, chert, greenstone, and serpentinite, as well as exotic blocks metamorphosed to the blueschist facies.

Volcanic eruptions in the Clear Lake-Geysers area began at about 2.1 Ma (Donnelly-Nolan et al., 1981), although the associated intrusive activity may have begun as early as 2.5 Ma (Schriener and Suemnicht, 1981). Beneath The Geysers a composite pluton, informally known as the "felsite", reaches to within approximately 0.7 km of the surface (Schriener and Suemnicht, 1981, Thompson, 1989). This pluton consists of three major intrusive phases (Fig. 1; Hulen and Nielson, 1993) that together have a volume in excess of 100 km^3 (Thompson, 1989; Donnelly-Nolan et al., 1993). These rocks have yielded $^{40}Ar/^{39}Ar$ ages ranging from more than 1.3 to 0.95 Ma (Pulka, 1991; Dalrymple, 1992). A still younger intrusive event is represented by a 0.57 Ma rhyolite dike that was emplaced in the southeastern part of the field (Pulka, 1991). Other, younger intrusives may be present beneath the northern part of the field as suggested by measured temperatures up to 342°C (Walters et al., 1988) and high $^3He/^4He$ ratios (R/Ra values to 8.3; Truesdell et al., 1994). These intrusives may be part of a larger body of molten or partially molten rock that is believed to be centered beneath Mt. Hannah (Isherwood, 1981), northeast of the steam field.

3. HYDROTHERMAL ALTERATION

Alteration of Franciscan Assemblage rocks at The Geysers is related to two major events: early subduction-related regional metamorphism and later contact metamorphism and hydrothermal alteration resulting from intrusion of the pluton. This early regional metamorphism altered the Franciscan graywackes, rocks consisting mainly of quartz (35-40%), plagioclase feldspar (25-35%), and sheet silicates (15-30%).

Within 300 to 600 m of the intrusive contact, the metagraywackes have been transformed to a biotite hornfels containing quartz-biotite-plagioclase-orthoclase + ilmenite/

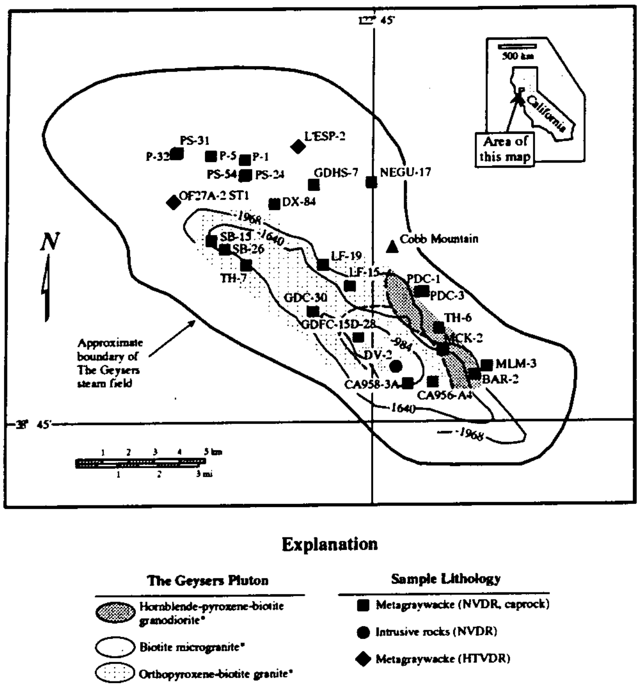


Figure 1 - Map of The Geysers pluton showing the distribution of the major intrusive phases (modified from Hulen and Nielson, 1993, and Thompson, 1989), the locations of the wells discussed in the text, and the lithologies of the samples studied. The contours show the elevation of the pluton in Abbreviations: BAR = Barrows; LF = Lakoma Fame; L'ESP = L'Esperance; MCK = Mckinley; P = Prati; PS = Prati State; SB = Sulphur Bank; and THR = Thorne. The following refer to regions of the present steam reservoirs: NVDR = normal vapor-dominated reservoir; caprock; and HTVDR = high-temperature vapor-dominated reservoir.

magnetite + tourmaline + pyroxene + tremolite/actinolite. Porphyroblasts of tourmaline in the hornfels provide evidence that boron-rich fluids infiltrated the rock during contact metamorphism. Throughout the hornfels, biotite is commonly altered partially to chlorite; pyroxene to actinolite and chlorite; and plagioclase to sericite. Sulfides are rare to uncommon in the hornfels; they seldom account for more than a trace of the total rock volume, but locally are present in amounts up to 2 wt%. The sulfides include pyrite, pyrrhotite, chalcopyrite, bornite, sphalerite, and galena in various combinations.

Extending outward from the pluton for up to 2.5 km is a broader halo of hydrothermal alteration and vein mineralization. Alteration and vein-mineral assemblages are strongly temperature-dependent, reflecting proximity to the pluton. The veins have been divided into five stages based on cross-cutting relationships or distance from the intrusion. Within the hornfels, stage 1 veins consist of tourmaline and/or biotite ± actinolite ± clinopyroxene ± potassium feldspar ± quartz. Two types of biotite have been recognized — an earlier, reddish-brown, relatively coarse-crystalline variety; and a later, brownish-green to green microcrystalline variety. Veins with the green biotite are quite rare and so far confined to the northwestern portion of the The Geysers, but where present, they also contain trace to minor amounts of chalcopyrite and bornite along with pyrrhotite. These veins are reminiscent of those found in many porphyry copper ore deposits (Hulen and Nielson, 1993; Hollister, 1978). The portion of The Geysers hydrothermal system explored to date appears to have been too sulfide-deficient to form an "ore-grade" concentration of copper sulfide minerals. However, the presence of these clearly porphyry-copper-style, secondary-biotite-bearing veins in some of the field's deeper cores suggests that such a deposit could have formed elsewhere within the Clear Lake volcanic field.

With increasing distance from the pluton, veins with the following key mineral assemblages disrupt the Franciscan-Assemblage rocks: Stage 2 — Actinolite ± ferroaxinite ± epidote ± potassium feldspar ± quartz; Stage 3 — Epidote ± chlorite ± potassium feldspar ± quartz ± wairakite; Stage 4 — Calcite (typically the "bladed" variety) ± potassium feldspar ± quartz ± datolite; and Stage 5 — Mixed-layer illite/smectite and chlorite/smectite, which was apparently precipitated by acidic condensate above the modern vapor-dominated system. These latest-stage clays are believed to be a major factor in the formation of the caprock overlying the steam reservoir. Trace to minor amount of sulfide minerals are locally present in veins of all stages. The sulfides in stage 1-4 veins comprise pyrite, pyrrhotite, chalcopyrite, galena, and sphalerite in various combinations. Pyrite appears to be the sole sulfide in stage 5 veins.

Hydrothermal alteration of The Geysers' reservoir rock is concentrated in selvages along hydrothermal veins. Where these selvages coalesce, the entire rock volume may be so affected. Alteration of the Franciscan-Assemblage rocks is typically sericitization and/or potassium-feldspar replacement and epidotization of rock-forming albite accompanied by chloritization of mafic minerals and deposition of trace to minor amounts of disseminated pyrite.

The Geysers pluton is also variably altered. In much of the pluton, particularly in the southeastern portion of the field, feldspars remain fresh, and only original orthopyroxene is hydrothermally altered to chlorite or actinolite ± epidote. By contrast, in the northwestern portion of the field, mafic minerals are intensely chloritized, and both mafics and plagioclase are locally but extensively altered to tourmaline and ferroaxinite. This ferroaxinite is believed to be a replacement of the original tourmaline. In the south-central Geysers, where the pluton is shallowest, alteration is characterized by locally intense sericitization superimposed on weaker and more erratically distributed chlorite-tourmaline-potassium feldspar-quartz alteration.

Hydrothermal dissolution of Franciscan calcite appears to have formed much of the porosity in which the liquid water reserves of The Geysers occur (Thompson and Gunderson, 1992; Hulen et al., 1991). Calcite or aragonite commonly account for 2-3 weight per cent of the Franciscan-Assemblage rocks on a regional basis. Dissolution of these carbonates, therefore, enhances the porosity of rocks which are intrinsically non-porous. If the volume of The Geysers reservoir is about 600 km^3 (Williamson, 1992), and, say, 400 km^3 is hosted by Franciscan rocks, then carbonate dissolu-

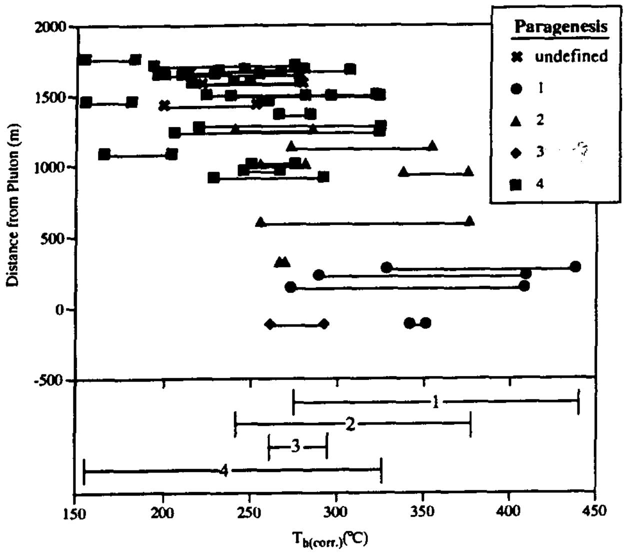


Figure 2 - Pressure-corrected homogenization temperatures ($T_{h(corr.)}$(°C)) with respect to distance from the pluton. The horizontal lines connect the minimum and maximum temperatures from each depth interval studied. The vein assemblages are shown by the solid symbols. See text for the definition of each vein paragenesis. The lower portion of the diagram summarizes the range of temperatures associated with each vein assemblage.

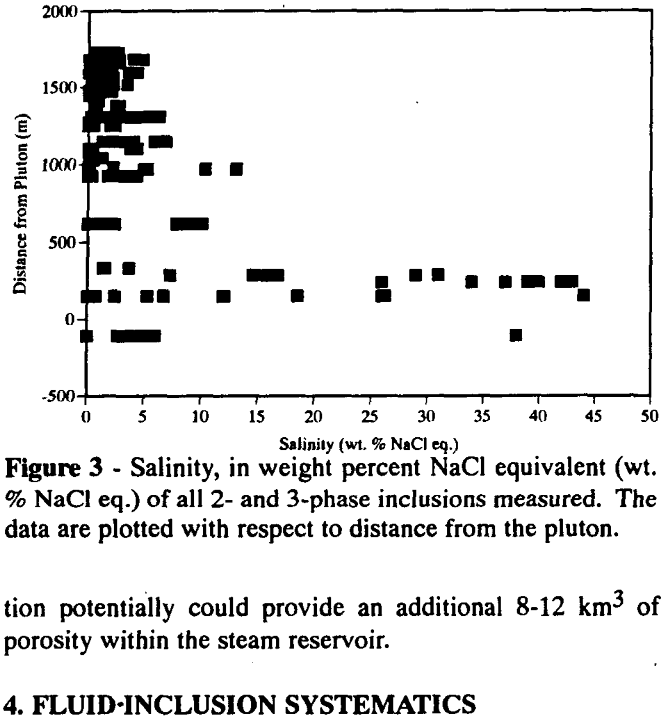


Figure 3 - Salinity, in weight percent NaCl equivalent (wt. % NaCl eq.) of all 2- and 3-phase inclusions measured. The data are plotted with respect to distance from the pluton.

tion potentially could provide an additional 8-12 km^3 of porosity within the steam reservoir.

4. FLUID-INCLUSION SYSTEMATICS

Fluid inclusions were measured in core and cuttings samples from 33 intervals in 24 wells at The Geysers (Fig. 1). The inclusions were found in quartz, calcite, epidote, and actinolite. Most of the measurements were made on 2-phase liquid-rich inclusions although 2-phase vapor-rich inclusions, and 3- and 4- phase inclusions that contained halite or halite and sylvite were also measured. The solid-bearing inclusions are restricted to the hornfels and plutonic rocks.

The vast majority of the inclusions studied were secondary in origin, occurring along healed fractures. Primary inclusions are relatively uncommon, and when found define growth zones or are intimately associated with solid inclusions of calcite encapsulated in quartz. No pseudosecondary inclusions could be identified on the basis of petrographic relationships. However, primary and secondary inclusions commonly display similar homogenization temperatures, indicating that these secondary inclusions formed during crystal growth.

Figure 2 shows the pressure-corrected homogenization temperatures with respect to distance from the pluton. Remnants of volcanic rocks that are contemporaneous with intrusive activity suggest that the paleosurface was at an elevation of 950 m msl (mean sea level) at the time the inclusions were trapped. Lithostatic pressures were used to correct temperatures of 2- and 3-phase inclusions from the pluton and hornfels. Independent evidence for the development of lithostatic pressures is provided by the experimental data of Bodnar (1994), which indicates that inclusion from a depth of -2203 m msl must have been trapped at pressures of at least 800 bars. The calculated lithostatic pressure at this depth is 835 bars. In contrast, the temperatures of 2-phase liquid-rich inclusions from rocks above the hornfels were corrected assuming that pressures were hydrostatic. We have used these lower pressures because the corrected temperatures generally do not exceed boiling point to depth curves drawn for the appropriate salinities.

Figures 2 and 3 show that the pressure-corrected homogenization temperatures and apparent salinities of the hydrothermal fluids ranged from 440°C and 44 weight percent NaCl equivalent within the hornfels (<600 m from the pluton) and intrusive rocks to 325°C and 5 weight percent NaCl equivalent at distances of approximately 1500 m from the intrusion. These salinity-temperature relationships suggest the fluids may have several different origins. The high salinities and temperatures of the halite-saturated inclusions (>26 weight percent NaCl equivalent) are indicative of magmatic brines. The origin of the shallow, moderate-salinity fluids is more problematic. The salinities of these waters are higher than would be expected for geothermal systems dominated by meteoric waters. We suggest, that these moderate-salinity waters represent crustal (connate or metamorphic) fluids modified by water-rock interactions. Irrespective of their origin, the data demonstrate that fluid inclusions trapped within the present steam reservoir display no evidence of cooling below the current reservoir temperature of 240°C. This observation suggests that the steam reservoir developed directly from the earlier liquid-dominated hydrothermal system defined by the fluid-inclusion data.

A record of the initial development of the vapor-dominated regime appears to be found in the low salinity inclusions (0 to 4 weight percent NaCl equivalent) that are common in the caprock but also occur to a lesser extent in the reservoir rocks. The high temperatures and low salinities of these inclusions suggest that the inclusion fluids are not simply meteoric water. This conclusion is supported by data from well McKinley-2, where homogenization temperatures of inclusions with salinities of 0.0 weight percent NaCl equivalent ranged from 248° to 264°C while inclusions with salinities greater than 4.6 weight percent NaCl equivalent had temperatures that ranged from 234° to 246°C. The persistence of these high salinity fluids to lower temperatures indicates that the hydrothermal fluids in this part of the field had not been displaced by meteoric waters when the low salinity fluids were trapped.

Instead, we suggest that the low salinity inclusion fluids (0 to 4 weight percent NaCl equivalent) represent condensate formed during the initial boiling off of the precursor liquid-dominated hydrothermal system. With few exceptions, the maximum temperature of condensation ranged from 250° to 265°C and appears to have varied little with depth or location within the field. Thus, the data suggest that a heat pipe may already have developed at the time the inclusions were trapped.

Direct evidence of widespread boiling and the formation of an acidic condensate is present in the upper 300 m of the reservoir and the overlying caprock. Here, boiling resulted in the formation of bladed calcite (e.g. Tulloch, 1982) and the coprecipitation of calcite and quartz while the subsequent corrosion of the calcite and the formation of late-stage clays (Moore et al., 1989; Hulen et al., 1991) record the presence of condensate. At greater depths within the reservoir, clear mineralogic evidence of boiling is lacking and this process appears to be represented only by the presence of vapor-rich and low-salinity inclusions.

In contrast, the origin of the dilute, lower temperature inclusions (< about 200°C) is less clear. These fluids may in part represent meteoric recharge to the thermal system. Such an origin, which is discussed in more detail below, is suggested by CH_4-N_2-Ar ratios of some inclusions from the southeast part of The Geysers (Norman and Moore, 1994).

5. FLUID-INCLUSION GAS COMPOSITIONS

Fluid-inclusion gases were analyzed by quadrapole mass spectrometry for 12 samples from 9 wells and from one sample of a pregeothermal aragonite + lawsonite vein from Elk Mountain. The gases were released from the inclusions by thermal decrepitation at temperatures of 400° to 500°C. Figure 4 shows the relationships between Ar, He, and N_2 in the samples studied. The ratios of these gases can be used as an indicator of their source (Giggenbach, 1986; Norman and Musgrave, 1994). For example, high He values are typical of crustal or connate waters while high Ar concentrations characterize meteoric waters. Magmatic gases are characterized by high N_2 contents.

The gas data shown in Figure 4 indicate that most of the reservoir samples and a few from the caprock plot near the N_2 corner, suggesting that these gases have a magmatic origin. Such an origin is supported by the presence of hypersaline brines in some of these samples. However, the presence of N_2-rich gases in samples from the caprock and normal vapor-dominated reservoir that contain only low- to moderate-salinity waters indicates that the movement of the gases was not coupled to that of the liquids. The remaining samples, which display a much larger range of gas ratios, are dominantly from the caprock. These samples may contain varying proportions of magmatic, connate, and meteoric gases.

The gas compositions of the fluid inclusions are compared to those of representative analyses of the present-day steam in Figure 5 from The Geysers and of springs located outside the productive portions of the field. In this plot, CH_4 substitutes for He as a possible indicator of crustal fluids. These data indicate that the percentage of air-saturated water in the steam increases from the northwest to the southeast. Truesdell et al. (1987) showed that the stable isotope compositions of the steam also indicated that recharge was greatest in the southeast portion of the field.

Figure 5 demonstrates that the fluid-inclusion gas ratios are very similar to those of the steam, with the majority plotting near steam from the northwest part of the field. These samples are characterized by relatively low Ar contents, and thus, show little evidence of a meteoric component. The spring data and the sample from Elk Mountain also plot in this region of the diagram, supporting the conclusion that the fluid inclusion gases are dominantly crustal or connate in origin. A significant meteoric component only appears to be present in two samples, both of which are from the caprock in the southeast part of the field.

6.0 CONCEPTUAL MODEL OF THE SYSTEM

The mineralogic and fluid inclusion data indicate that the present vapor-dominated regime at The Geysers developed from a more extensive liquid-dominated hydrothermal system. In the following sections, we summarize the major features of each of the key evolutionary stages in its development.

6.1 Initial Development of The Geysers Hydrothermal System

The development of The Geysers hydrothermal system began between about 1.5 and 2 Ma in response to emplacement of a composite granitic pluton that reached to within approximately 1 km of the paleosurface. Magmatic fluids with salinities up to approximately 44 weight percent NaCl equivalent circulated through the intrusive rocks and the biotite-rich hornfels within 300 to 600 m of the intrusive contact. Gases trapped within these inclusions are consistent with a magmatic origin and display enrichments in N_2 relative to He and Ar. In contrast, salinity data suggest that the fluids which circulated through the metagraywackes at greater distances from the pluton were crustal in origin.

6.2 Intermediate Stages in the Development of the System

As the hydrothermal system evolved and cooled, downward movement of fluids toward the intrusive contact occurred. Within the plutonic rocks and hornfels in the central and southeastern Geysers, moderate-salinity crustal waters replaced the earlier magmatic fluids. In the outer parts of the system, these crustal waters may have been locally replaced by meteoric recharge, as indicated by the presence of dilute

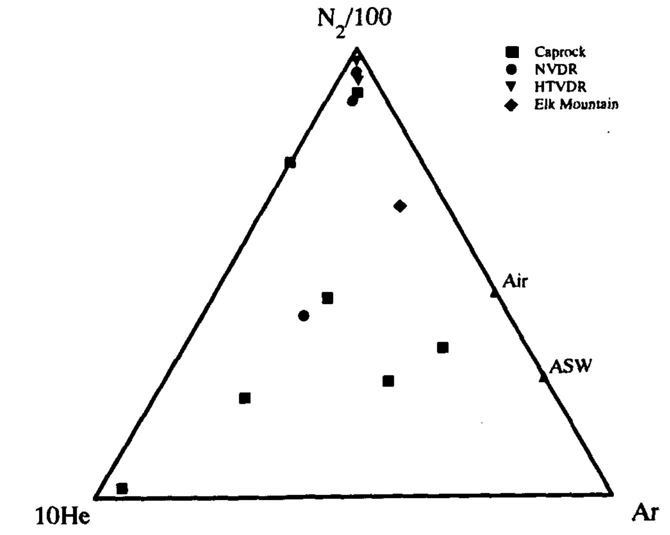


Figure 4 - Ternary plot showing N_2/100-10He-Ar ratios of fluid inclusions from the caprock, normal vapor-dominated reservoir (NVDR), high-temperature vapor-dominated reservoir (HTVDR), and from an aragonite-lawsonite vein of Franciscan age from Elk Mountain. ASW represents air-saturated water.

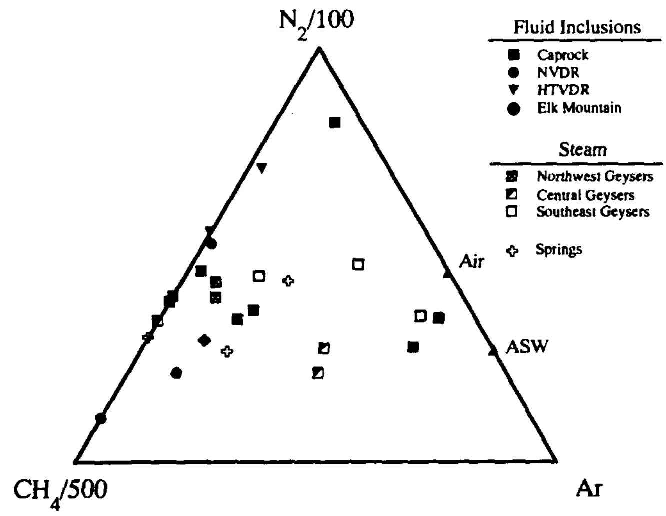


Figure. 5 - Ternary plot showing N_2/100-CH_4-Ar ratios of fluid inclusions, steam, and springs, from The Geysers and adjacent regions. Steam analyses from Truesdell et al. (1987); spring data from Goff and Janik (1993). Abbreviations as in Figure 4.

inclusion fluids with temperatures below 200°C, and gases enriched in Ar.

A reduction in the marginal permeabilities of the system may also have occurred at this time in response to the deposition of calcite by the downward percolating waters. White et al. (1971) argued that such a decrease in the original permeabilities of the system are needed because pressures within the present vapor-dominated reservoir are far below hydrostatic and thus, flooding of the reservoir would occur without an effective seal.

6.3 The Present Geothermal System

The present vapor-dominated regime at The Geysers consists of two distinct, hydraulically connected steam reservoirs. Within the main reservoir, temperatures are close to 240°C and pressures are vaporstatic. Beneath this reservoir, in the northern third of the field, temperatures as high as 342°C have been measured (Walters et al., 1988).

Fluid inclusions with salinities near 0 weight percent NaCl equivalent and homogenization temperatures close to 265°C record the development of the vapor-dominated system. These low-salinity fluids are interpreted as representing the slightly acidic condensate that formed as the early liquid-dominated hydrothermal system boiled off. Within the caprock and the upper 300 m of the reservoir, the boiling fluids deposited bladed calcite, quartz and potassium feldspar. As vapor-dominated conditions evolved, the acidic condensate etched the calcite and deposited illite, mixed-layer clays and locally kaolin (Moore et al., 1989; Hulen et al., 1991). At greater depths, clear mineralogic evidence for the boiling off of this early, liquid-dominated hydrothermal system is lacking, and this process appears to be represented only by the presence of vapor-rich fluid inclusions and inclusions that trapped condensate.

7. ACKNOWLEDGMENTS

This project would not have been possible without the support of the management and staff of the Calpine Corporation, Coldwater Creek Power Authority, and the Unocal Corporation. In particular we want to thank T. Box and J. Beall who made unpublished data and samples, some of which were painstakingly hand-picked by M. Stoh-Twichell available to us. Special thanks are due to J. Hulen who generously shared his ideas and observations on the hydrothermal alteration and plutonic rocks of The Geysers. Others who substantially contributed to this project and made many helpful suggestions during the course of the work include M. Adams, D. Cole, P. Dobson, P. Molling, B. Smith, and M. Walters. Funding was provided by the DOE under contract DEAC07-901D 12929.

8. REFERENCES

Bodnar, R. J. (1994) Synthetic fluid inclusions: XII. The system H_2O-NaCl. Experimental determination of the halite liquidus and isochores for a 40 wt% NaCl solution. *Geochim. Cosmochim. Acta,* 58, 1053-1063.

Dalrymple, G. B. (1992) Preliminary report on $^{39}Ar/^{40}Ar$ incremental heating experiments on feldspar samples from the felsite unit, Geysers geothermal field, California. *USGS Open-File Rept.* 92-407.

Donnelly-Nolan, J. M., Hearn, B. C., Jr., Curtis, G. 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* (ed. R. J. McLaughlin and J. M. Donnelly-Nolan); *USGS Prof. Paper,* 1141, 47-60.

Donnelly-Nolan, J. M., Burns, M. G., Goff, F. E., Peters, E. K., and Thompson, J. M. (1993) The Geysers-Clear Lake area, California — Thermal waters, mineralization, volcanism, and geothermal potential. *Econ. Geol.*, 88, 301-316.

Giggenbach, W. .F. (1986) The use of gas chemistry in delineating the origin of fluid discharges over the Taupo Volcanic Zone, A review. Proc. Intl. Volcanol. Congress, New Zealand, S. 47-50

Goff, F. and Janik, C. J, (1993) Gas geochemistry and guide for geothermal features in the Clear Lake region, California. In Fieldtrip Guidebook — *The Geysers geothermal area and the McLaughlin gold deposit, California* (ed. J. J. Rytuba); *Society of Econ. Geologists,* 16, 107-261.

Hollister, V. F., (1978) Geology of the porphyry copper deposits of the western hemisphere: New York, *Soc. Mining Eng., Am. Inst. Mining, Met., and Petrol. Eng.*, 219.

Hulen J. B. and Nielson, D. L. (1993) Interim report on geology and hydrothermal alteration of The Geysers felsite. Geotherm. *Resources Council Trans.*, 17, 249- 258.

Hulen, J. B., Walters, M. A., and Nielson, D. L. (1991) Comparison of reservoir and caprock core from the Northwest Geysers steam field, California. *Geotherm. Resources Council Trans.,* 15, 11-18.

Isherwood, W. F., 1981, Geophysical overview of The Geysers. In *Research in The Geysers-Clear Lake Geothermal Area, Northern California* (ed. R. J. McLaughlin and J. M. Donnelly-Nolan); *USGS Prof. Paper*, 1141, 83-95.

McLaughlin, R. J. (1981) Tectonic setting of pre-Tertiary rocks and its relation to geothermal resources in The Geysers-Clear Lake area. In *Research in The Geysers- Clear Lake Geothermal Area, Northern California* (ed. R. J. McLaughlin and J. M. Donnelly-Nolan); *USGS Prof. Paper*, 1141, 25-45.

McLaughlin, R. J. and Ohlin, H. N. (1984) Tectonostratigraphic framework of the Geysers-Clear Lake region, California. *Pacific Sec. Soc. Econ. Paleontologists Mineralogists*, 43, 221-254.

Moore, J. N., Hulen, J. B., Lemieux, M. M., Sternfeld, J. N., and Walters, M. A. (1989) Petrographic and fluid inclusion evidence for past boiling brecciation, and associated hydrothermal alteration above the Northwest Geysers steam field, California. *Geotherm. Resources Council Trans.* 13, 467-472.

Norman, D. I. and Moore, J. N. (1994) Fluid source tracing via fluid inclusion gas analysis in an evolving magmatic system: The Geysers California (abs.). *VII International Symposium on the Observation of the Continental Crust Through Drilling, Santa Fe, N.M., April 25-30.*

Norman, D.I. and Musgrave, J. A (1994) Ni-Ar-He compositions in fluid inclusions: Indicators of fluid source. *Geochim. Cosmochim. Acta* 58, 1119-1131.

Pulka, F. S. (1991) Subsurface geology at Ford Flat, Geysers geothermal system, California: M.S. Thesis, Houghton Michigan Tech.

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* (ed. M. L. Silberman, C. W. Field, and A. L. Berry); *USGS Open File Rept.* 81-355, 295-302.

Thompson, R. C. (1989) Structural Stratigraphy and intrusive rocks at The Geysers geothermal field. *Geotherm. Resources Council Trans.* 13, 481-486.

Thompson, R. C., and Gunderson, R. P., (1992) The orientation of steam-bearing fractures at The Geysers geothermal field in *Monograph on The Geysers geothermal field* (c. Stone, ed.): *Geothermal Resources Council, Special Report* 17, 65-68.

Truesdell A. H., Haizlip, J. R., Box, W. T. Jr., and D'Amore F. (1987) Fieldwide chemical and isotopic gradients in steam from The Geysers. Proc. *11th Wkshp. on Geotherm. Reservoir Eng., Stanford Univ.*, 241-246.

Truesdell A., Kennedy, M., Walters, M., and D'Amore, F. (1994) New evidence for a magmatic origin of some gases in *The Geysers geothermal reservoir. Proc. 19th Wkshp. on Geotherm. Reservoir Eng., Stanford Univ.*, in press.

Tulloch, A. J. (1982) Mineralogical observations on carbonate scaling in geothermal wells at Kawerau and Broadlands. *Proc. Pacific Geotherm. Conf.*, Part 1, 131-134.

Walters, M., and Combs, J. (1989) Heat flow in The Geysers-Clear Lake area of Northern California, U.S.A. *Geotherm. Resources Council Trans.*, 13, 491-502.

Walters, M. A., Haizlip, J. R., Sternfeld, J. N., Drenick, A. F., and Combs, J. (1988) A vapor-dominated reservoir exceeding 600° F at The Geysers, Sonoma County California. *Proc. 13th Wkshp on Geotherm. Reservoir Eng., Stanford Univ.*, 73-81.

White, D. E., Muffler, L. J. P., and Truesdell, A. H. (1971) Vapor-dominated hydrothermal systems compared with hot water systems. *Econ. Geol.* 66, 73-81.

Williamson, K. H., (1992) Development of a reservoir model for The Geysers geothermal field in *Monograph on The Geysers geothermal field* (c. Stone, ed.): *Geothermal Resources Council, Special Report* 17, 179-188.