Converging Evidence for Fluid Overpressures at Peak Temperatures in The Pre-Vapor-Dominated Geysers Hydrothermal System

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ABSTRACT

Peak paleotemperatures calculated from organic-matter reflectance for cores from The Geysers in many cases closely match corresponding fluid-inclusion trapping temperatures. When plotted relative to boiling point curves appropriate for (1) contemporaneous paleosurfaces; and (2) hydrostatic pressures and pressures required for natural hydraulic rock rupture, the peak temperatures suggest that the antecedent Geysers hot-water system was at least intermittently overpressured by several MPa. Such a system, when breached by tectonic fractures or hydrothermally fractured, would have vigorously boiled and vented. The venting, perhaps focused in the Sulphur Bank area of the steam field, in turn could have depleted much of the thermal fluid initially in place. This is an ideal scenario for inception of the vapor-dominated conditions which still prevail.

Introduction

The Franciscan Assemblage (Late Jurassic and Cretaceous), subduction-trench-related metaclastic rocks which host much of The Geysers steam field (Thomas et al., 1981; McLaughlin, 1981; Figure 1) are locally very rich in detrital organic matter. The organics include vitrinite (Underwood, 1989; Bostick, 1974), a substance derived from the woody parts of terrigenous plants. The reflectance of vitrinite (VR) increases systematically and irreversibly with time (sluggish, linear response) and temperature (rapid and geometrically increasing response) (Barker and Pawlewicz, 1994). VR can be measured very precisely and used to estimate the maximum temperature to which a rock has been subjected. The technique has been used for this purpose in several high-temperature geothermal systems around the world (summarized in Browne, 1993); the first geothermal application of VR was by Barker and Elders (1981) for the Salton Sea field in southern California.

Working with core from Sulphur Bank area borehole SB-15D at the Geysers (Figure. 1), Hulen and Moore (1996) compared VR peak paleotemperatures with those obtained from fluid-inclusion trapping temperatures as well as the temperature-sensitive expandable interlayer content of mixed-layer illite/smectite. The correlation among the three geothermometers at given depths was sufficiently satisfying that a similar but more detailed and field-wide study was soon begun.

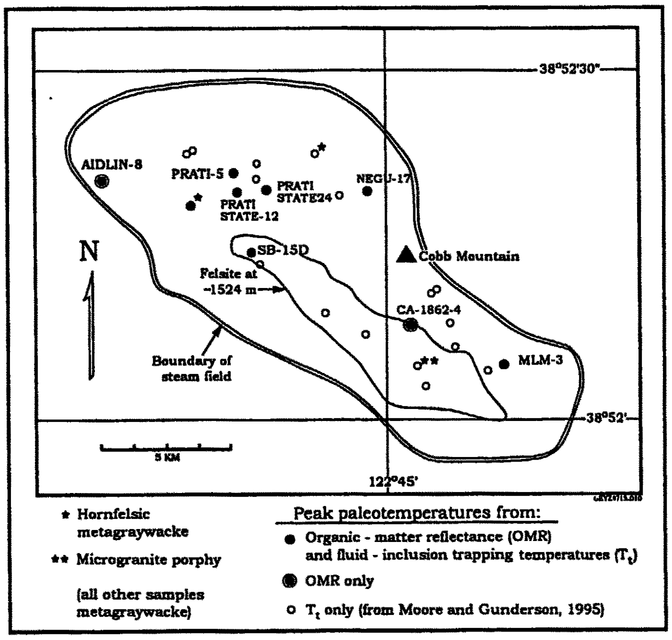

Figure 1. Location map

An important aim of the study was confirmation, for a large suite of samples, that VR could be a reliable geo-thermometer throughout The Geysers. If so, it could be applied at comparatively low cost for assessing paleotemperatures where fluid-inclusion microthermometry was impractical or impossible. Unfortunately this is the typical case at The Geysers, where the powdery consistency of the predominant air-drilled cuttings precludes fluid-inclusion work. A second goal of the study, assuming that VR was found viable for the field, was providing new constraints for models of The Geysers+ hydrothermal history—especially the transition from liquid-dominated to vapor-dominated conditions. The encouraging results of this investigation are presented and discussed in the text which follows.

Methods and Procedures

Eighteen core samples (from nine boreholes) retrieved by various steam-field operating companies and by the Department of Energy+s Geothermal Division (SB-15D) were analyzed for this investigation (Figure 1). Many of the cores had been studied previously for their fluid-inclusion systematics (Moore and Gunderson, 1995), yielding trapping temperatures which we could compare with values obtained from VR. Two cores, from wells Aidlin-8 and CA-1862-4, were generously donated by Calpine Corporation for this study. The locations of sixteen other cores with known fluid-inclusion trapping-temperature maxima (Moore and Gunderson, 1995) are also shown for reference.

For the VR work, a nominally 3 X 2 X 2 cm piece of each core was first crushed to about 10 mesh, and the resulting rock fragments embedded in epoxy. The specimens were ground, highly polished, and examined under reflected white light. Reflectance analyses were also completed on two Geysers polished sections obtained from Oak Ridge National Laboratory; because of their lower polish, these thin sections are believed to have provided less accurate VR data (accordingly not included for this report). For each sample examined, the mean reflectance (while immersed in oil) of vitrinite was converted to an equivalent peak paleotemperature using the equation of Barker (1991), derived empirically for young, organic-rich, deltaic sediments of the Salton Sea geothermal field:

$$T_{peak} = 132.8 \ln (VR/0.356)$$

Barker and Pawlewicz (1994) have developed a new empirical VR geothermometer for rapidly (geothermally) matured vitrinite, based on regression analysis of hundreds of VR measurements plotted against both measured and fluid-inclusion temperatures. We believe that the modern measured temperatures, where they unambiguously represent a rock+s thermal maximum, are far superior to fluid-inclusion trapping temperatures for comparison with VR. A fluid-inclusion trapping-temperature maximum conceptually could represent just the peak temperature of a younger and cooler thermal episode, and therefore be inappropriate for calibrating the VR value "locked in" at an earlier time.

Results

Analytical results for this study are displayed by Table 1, on which the boreholes are identified; core elevations reported; type of organic matter characterized; and multiple organic-matter-reflectance measurements correlated empirically with peak paleotemperatures.

Fifteen of the samples contain vitrinite, although the small particle size of this substance in eight of the cores precludes absolute confidence in its identification. These eight occurrences

Table 1. Locations, elevations, sample types, vitrinite (or pyrobitumen) reflectance, and paleotemperatures for core samples from The Geysers steam field. For locations, please refer to Figure 1. Pyrobitumen temperatures are provisional, determined as outlined in text.

	Drillhole	Sample elevation (m)	Specimen type	Measured component	n	%Ro	σ	Calculated peak paleotemperature,°C Range	Mean
	SB15-D	316	rock mount	equivocal vitrinite	41	3.14	0.23	279 - 299	289
	SB15-D	154	rock mount	vitrinite	14	3.25	0.23	284 - 303	294
1	SB15-D	129	rock mount	equivocal vitrinite	35	3.93	0.29	309 - 328	319
	SB15-D	122	rock mount	vitrinite	19	3.37	0.17	292 - 305	299
	SB15-D	119	rock mount	equivocal vitrinite	24	3.71	0.24	302 - 320	311
	SB15-D	101	rock mount	vitrinite	41	4.02	0.28	312 - 331	322
2	CA1862-4	-328	rock mount	pyrobitumen	33	4.34	0.27	335 - 355	345
3	Prati State 24	-405	rock mount	vitrinite	36	2.88	0.18	269 - 286	278
4	Prati 5	-479	rock mount	vitrinite	20	4.43	0.26	327 - 342	335
	MLM-3	-676	rock mount	equivocal vitrinite	54	4.45	0.25	328 - 343	335
5	MLM-3	-676	rock mount	equivocal vitrinite	12	4.12	0.44	311 - 339	325
	MLM-3	-676	rock mount	equivocal vitrinite	57	4.17	0.34	315 - 337	327
	Prati State 12	-1095	rock mount	vitrinite	52	3.95	0.34	307 - 331	320
6	Prati State 12	-1095	rock mount	equivocal vitrinite	22	4.26	0.27	321 - 338	330
	Prati State 12	-1095	rock mount	pyrobitumen	22	3.73	0.47	307 - 340	325
	OF27A-2	-2203	rock mount	pyrobitumen	20	6.15	0.34	395 - 420	410
7	Aidlin-8	-2487	rock mount	equivocal vitrinite	49	3.18	0.39	273 - 306	291

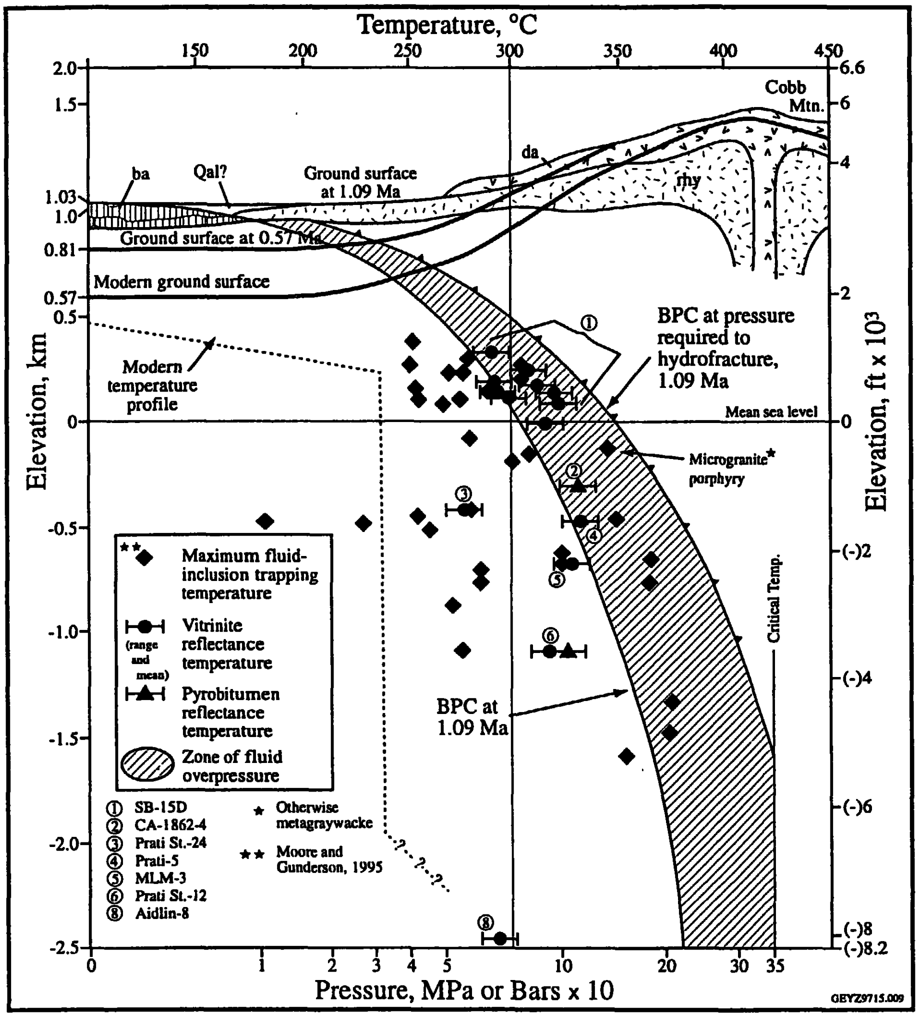

Figure 2. Peak paleotemperature vs depth for The Geysers hot-water dominated hydrothermal system (antecedent to the modern steam reservoir). Shown for reference are boiling-point curves (BPC) at hot-hydrostatic pressures, and at pressures required for natural hydraulic rock rupture. The water table is assumed to be at the contemporaneous paleosurface, belived to have been a slightly more than 1 km elevation at 1.1 Ma. Please refer to text for further explanation.

were designated "equivocal vitrinite" (Table 1). In some samples, (pyro)bitumen, a solidified, formerly liquid hydrocarbon, occurs with or without vitrinite.

Like vitrinite, the reflectance of solid bitumen also increases with increasing temperature, and is useful for evaluation of thermal maturity. Correlations between VR and bitumen reflectance (BR) have been established (Jacob, 1989; Landis and Castaño, 1995; Bertrand, 1993), but the validity of these correlations in hydrothermally heated rocks remains to be confidently established.

For this study the BR temperatures for cores from Prati State 12 and OF27A-2 (Table 1; Figure. 1) were arbitrarily set at, respectively, the peak paleotemperatures indicated by coexisting vitrinite; and the peak paleotemperatures indicated by trapping temperatures for highly saline magmatic-hydrothermal fluid inclusions. The latter are constrained on the basis of strong geologic evidence to have been trapped in the rock under semi-ductile conditions at lithostatic pressures during the earliest and hottest phase of The Geysers hydrothermal system (Moore and Gunderson, 1995). The values for these two cores were used to prepare a provisional VR vs BR crossplot. The BR value for CA-1862-4 (Table 1; Figure. 1) was simply taken from this graph. Its corresponding paleotemperature maximum, 345°C, is consistent with the presence of hydrothermal clinopyroxene and garnet in veins cutting the organic-rich host rock.

The VR and BR values obtained for this investigation are plotted relative to maximum fluid-inclusion trapping temperatures (Moore and Gunderson, 1995), at the true elevations of the samples, on Figures 2 and 3, which are identical except for hypothetical boiling-point curves (BPC) emanating from two different postulated ground surfaces. The significance of these BPC is discussed later in this paper.

Constraints for the paleo-elevations of these ground surfaces are as follows: The principal igneous intrusion (and likely magmatic heat source for the hydrothermal system) beneath The Geysers, a granodiorite, is the same age and composition (even to subtle trace-element concentrations and patterns) as the dacite of Cobb Mountain (1.1 Ma; Hulen et al., 1997), a prominent unit in the southern part of the Clear Lake volcanic field (Hearn et al., 1995). Thus the ground surface around Cobb Mountain at the time the dacite was erupted was probably close to the elevation prevailing when the early Geysers liquid-dominated hydrothermal system was initiated (though there could have been a "lag time" of a few tens of thousands of years

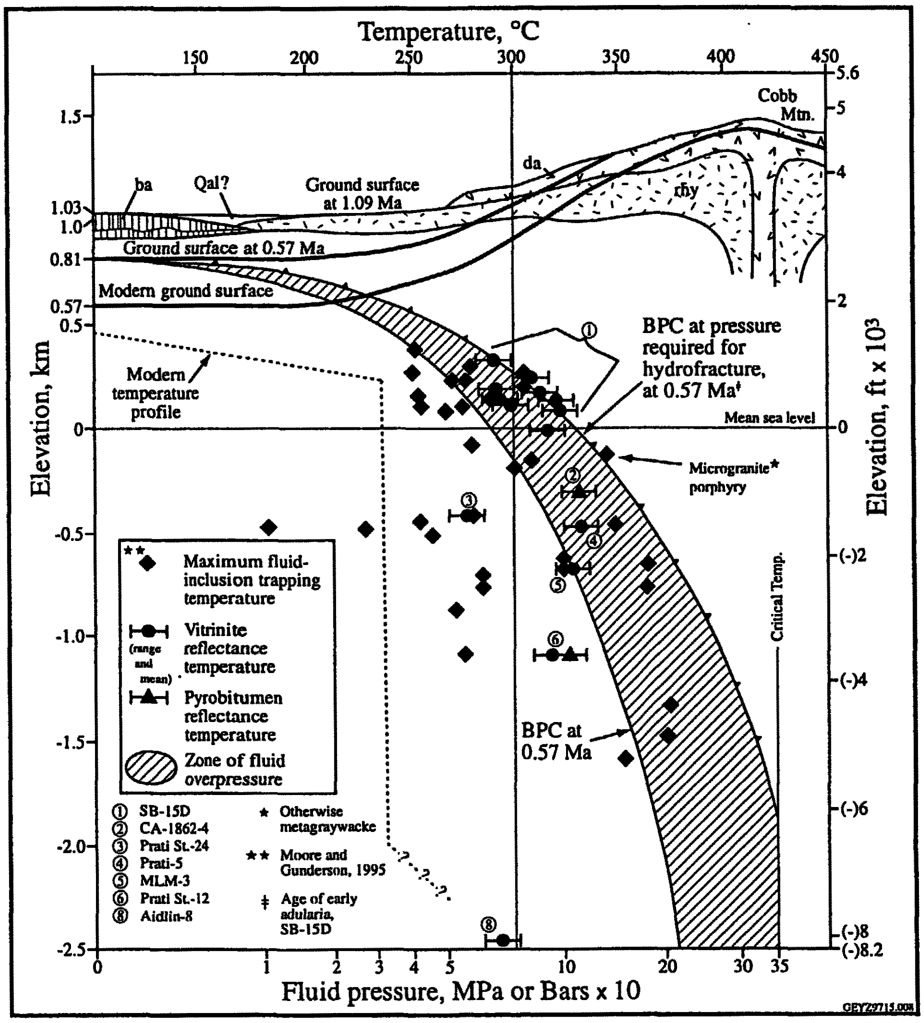

Figure 3. Same as Figure 2, but with the boiling-point curves emanating from a lower-elevation paleosurface, 810 m, believed to represent ground level at the Sulphur Bank area of The Geyser at 0.57 Ma. Please refer to text for further explanation.

between the time of intrusion and the time at which the hydrothermal system had been fully established). Several other Clear Lake volcanic units in the area, for example the 2.1 Ma Pine Mountain rhyolite (not shown), the 1.2 Ma rhyolite of Alder Creek, and the 1.6 Ma basalt of Caldwell Pines (Hearn et al., 1995; Turrin et al., 1994), also rest upon a paleosurface of about this elevation. We cannot rule out the possibility that the contemporaneous ground surface was as deeply dissected and rugged as it is now, but it seems more than coincidental that the currently remaining "scabs" of volcanics at The Geysers were all deposited at about the same elevation. Though much uncertainty attends this analysis, for the purposes of this paper we will assume that the topography between 1 and 2 Ma approximated a broad peneplain, upon which, beginning at 1.2 Ma, the highly localized Cobb Mountain volcano was developed. The reader should be aware that the apparent dominance of the ancient landscape by the volcano as it is portrayed on Figures 2 and 3 is an artifact of the graphic. The actual volcano occupied only about 10% of the present areal extent of the steam field. Placement of the ground surface at 0.57 Ma is based in large part upon a 40Ar/39Ar age for early vein adularia from SB-15D (Figure. 1; Hulen et al., 1997). We have shown the paleosurface at 1.1 Ma to have been probably at a little over a km above mean sea level. We also know the present elevation at SB-15D (570 m), and these values constrain an average erosional rate since eruption of dacite from the Cobb Mountain volcano. The rate is 0.42 mm/yr, which in turn would have placed the 0.57 Ma paleosurface at 810 m.

Discussion and Conclusions

Not surprisingly in view of prior fluid-inclusion work (Moore and Gunderson, 1995), VR and BR values for the analyzed Geysers cores are exceptionally high, significantly above regional VR background values for the Franciscan Assemblage. For example, both to the north and south of the steam field, equivalent Franciscan metaclastic rocks show VR values of 0.6 to 1.8% Ro (Underwood, 1989; Bostick, 1974). Utilizing the Barker and Pawlewicz (1994) deep-burial VR geothermometer, these values correspond to regional peak paleotemperatures of 95-184°C (mean 136°C). This is significantly lower than the corresponding ranges of 130-230°C (mean 180°C) and 120-260°C (mean 190°C) determined, respectively, by Bostick (1974) and Price (1983; in Underwood, 1989).

There is some question about the validity of applying "deep burial" VR geothermometers to rocks which have undergone high-pressure blueschist-grade metamorphism (e.g. McLaughlin, 1981). However, no matter which of these geothermometers is applied, the maximum indicated regional peak paleotemperatures for the sorts of rocks which host The Geysers are significantly less than those determined for the steam field itself (Table 1; Figures 2 and 3).

The two sets of BPC shown on Figures 2 and 3 are constructed for a 5 wt% NaCl solution (see Moore and Gunderson, 1995) and for (1) simple hot-hydrostatic pressures and (2) pressures required to induce natural hydraulic rock rupture in an extensional tectonic regime (see Oppenheimer, 1986, for evidence in support of such a regime at The Geysers). The latter values are essentially one-third of twice the cold-hydrostatic pressure plus the lithostatic pressure (Hubbert and Willis, 1957). When fluid pressures exceed this value, they are sufficient to break the rock hydraulically.

Plotted relative to the two BPC on each figure are paleotemperature maxima as determined from fluid-inclusion trapping temperatures (Moore and Gunderson, 1995; Moore et al., 1989) and organic-matter reflectance (this study). It can be seen at a glance that, even assuming the higher-elevation paleosurface, a significant fraction of the thermal maxima correspond to an overpressured fluid field between the two BPC.

In general, the thermal maxima that are lower than normal BPC values for a given elevation correspond to cores from the flanks of the field, away from the northwest-trending "spine" of the felsite (Figure. 1), the presumed igneous heat source for The Geysers (Hulen and Nielson, 1996). We believe it likely that isotherms in the pre-steam Geysers hydrothermal system away from the felsite "spine" had more vertical separation than their counterparts directly above the intrusion; in other words, the isotherms "arched" over the felsite at the time the causative hot waters were in circulation (see also Moore and Gunderson, 1995). The VR, BR, and fluid-inclusion thermal maxima which plot in the overpressured field of Figures 2 and 3 are in general from cores above and along the crest of the felsite, where the hydrothermal system presumably was most vigorous and reached to its highest elevations.

This being so, it would seem that The Geysers hot-water system was, at peak paleotemperature, at least intermittently "primed" to boil vigorously and vent if breached by fractures. It is even possible that in the Sulphur Bank area (where SB-15D was drilled), where the paleosurface appears to have been at 810 m at 0.57 Ma (Figures 2 and 3), such venting and boiling may have been induced by natural hydraulic rock rupture. Speculation along these lines for The Geysers first appeared in print in the 1980's (Thomas et al., 1981; Hebein, 1985 and 1986). The new data suggest that such hydrothermal explosions may in fact have taken place. We believe it quite likely that the postulated ensuing venting of the Geysers hot-water system could have depleted a significant fraction of the thermal fluid initially in place. Such fluid depletion, in turn, has been cited by Pruess (1985) and Shook (1995) as directly responsible for establishment of the vapor-dominated conditions which still prevail at The Geysers.

An intriguing new finding of this study is the apparent close correspondence of VR peak paleotemperature and modern reservoir temperature for the core from the deep Aidlin "high-temperature" reservoir (core from Aidlin-8; Table 1; Figures 2 and 3). Elswhere in the northwest Geysers, the high-temperature vapor-dominated reservoir (with temperatures as high as 340°C) is developed in Franciscan metaclastic rocks which have been contact-metamorphosed to biotite-oligoclase-tourmaline-orthoclase assemblages in a halo around The Geysers felsite (Walters et al., 1992). By contrast, the Aidlin-8 core is more typical of the "normal" Geysers reservoir, being veined with calc-silicates like axinite, actinolite, and epidote, but not converted to hornfels.

Maximum fluid-inclusion paleotemperatures for the few available samples of the hornfels-hosted high-temperature steam reservoir approach 450°C, far in excess of the corresponding modern temperatures at these depths (generally 275-285°C). In other words, modern temperatures represent a drop from the maximum of more than 150°C.

By contrast, whereas the current reservoir temperature at the depth of the Aidlin-8 core is believed to be somewhere between 275°C and 290°C; the mean VR peak paleotemperature for the rock is 291°C (Table 1). This means that the Aidlin high-temperature reservoir in fact may now be at its thermal maximum. If this proves to be the case, the deep Aidlin reservoir would constitute a unique natural laboratory for studying high-temperature steam-reservoir formation perhaps at the very inception.

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