Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Crustal Thermal Regime at The Geysers/Clear Lake Area, California

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Keywords: The Geysers, heat transfer, modeling, magma

ABSTRACT

The Geysers/Clear Lake area in northern California is characterized by extensive volcanism and intrusion of bimodal magmatic products within the last 2 Ma and by the presence of one of the largest (steam dominated) geothermal systems in the world. Based on a compilation of data from over 650 heat flow sites in 100 to 600 m wells, the region is also characterized by a large area of elevated regional heat flow (an area greater than 1,600 km^2). The heat flow over this large area averages 150 mW/m^2, about double the already high Coast Range regional heat flow of 75 mW/m^2. Temperature-depth data from numerous deep wells (average 3 km) demonstrate characteristics of the thermal regime in this magmatic/volcanic system to depths where the temperatures are 250 to 350 °C. One of the characteristics of vapor dominated systems is their low permeability. Thus the large thermal data set and the very low permeability of the upper crust in this region allow a look at the upper and mid-crustal thermal effects of a large scale intrusive center with limited surface expression. Two dimensional forward and a 3-d inverse thermal models of the intrusions (varying both in size and frequency, based on the present day heat flow pattern and the igneous record of the last 2 M.Y.) that underlay this upper crustal system are described. The heat flow and deep temperature data are powerful constraints on the interesting parameters that are otherwise only known from fossil systems, not currently active, large, cryptic, magmatic systems. The rate of intrusion is on the order of 0.005 km^3/yr which is slow enough to allow for significant cooling so that most of the upper crust is below magmatic temperatures for most of the time. This region of thermal disturbance is characterized by a negative gravity anomaly and by shallowing of the seismogenic layer. Direct seismic evidence of magma has not been identified, but nonetheless this area represents an active plutonic system in a geologic sense.

1. INTRODUCTION

The detail of the relationship between magmas and geothermal systems is a complicated one and is not well understood. This is particularly the case when the magma system is not clearly identified. Large silicic magma chambers are abundant in the geologic record, but their connection to shallow conditions is enigmatic and their modes and rate of cooling largely unknown. If they are connected to caldera systems the surface presence is easy to recognize. However, in systems with minor to no surface volcanism the relationship is much less easy to understand. Two areas that would not *a priori* attract attention as the sites of large intrusive features are The Geysers in northern California (White et al., 1971) and Lardarello in the Tuscany region of northern Italy (Bellani et al., 2004), two of the largest geothermal fields in the world. The main evidence for the presence of large scale plutonism is the massive heat loss associated with them because the volcanic volume is small at The Geysers (about 100 km^3 over 2 Ma, Donnelly-Nolan et al., 1993), and nonexistent at Lardarello.

The Geysers system has been described in detail from a production point of view in (see for example papers in Stone, ed., 1992 including Williamson, 1992; Barker, 1992). One of the important results of the exploitation is the drilling of many shallow thermal gradient wells (over 600 are used here) and over 200 deep wells. Some of the wells reach temperatures of over 300°C (Walters et al., 1992). Temperatures this high are very significant in the evaluation of the evolution of the cooling magma body (or bodies). They also represent temperatures near the brittle/ductile transition, i.e. base of the seismogenic zone.

The geology of The Geysers area is Mesozoic age Franciscan Terrain rocks, mostly shale, greywacke, and serpentinite (McLaughlin, 1981). There are several significant fault zones. The origin of these faults is not always clear as to whether they are part of the outer arc subduction setting of the Franciscan or the younger strike slip behavior associated with the San Andreas transform fault system. The most important of these are the seismically active Rogers Creek-Healdsburg-Maacama fault zone and Green Valley-Bartlett Springs fault zone. The Collayomi fault is between the other two and not now seismically active (Figures 1 and 2). The thermal anomaly is essentially confined between the first two faults and the Collayomi divides the area of the thermal anomaly into two parts with different surface geology (Franciscan basement versus late Cenozoic volcanics). The Geysers geothermal field southwest of the Collayomi fault is completely in Franciscan rocks. The production there is associated with fractured greywacke. The greywackes are quite quartz rich and have a bulk composition near granite. At depths greater than 2 km a granodiorite/quartz monzonite body is encountered in some wells (referred to as the felsite, see map in Stone, 1992; Norton and Hulen, 2001). K/Ar ages of about 0.5 to 1 Ma have been obtained from this buried body (Moore et al., 1995; Dalrymple et al., 1999; Schmitt et al., 2002). There is one large (9 km^2) rhyolite dome outcropping in the field area (Cobb Mt.) Northeast of the Collayomi fault most of the area is covered with a bimodal suite of Pliocene to Holocene age volcanics (the Clear Lake Volcanics, Walters and Combs, 1992, Donnelly-Nolan et al., 1981). The ages of these rocks range from 2 to 0.01 Ma (Hearn et al., 1981; Donnelly-Nolan et al., 1993; Stimac et al., 2001). On the east side of the Collayomi fault the preCenozoic basement consists of sedimentary rocks typical of the Great Valley sequence that are thrust over the Franciscian terrain (Stanley et al., 1998).

The area is part of the Coast Range Thermal Anomaly (CRTA) (Lachenbruch and Sass, 1980). The average heat flow in the area of the CRTA is about 75 mW/m^2 (regional heat flow sites diamonds, and values are shown on Figure 1). Although the regional heat flow is relatively well known, the transition from anomalous heat flow in The Geysers/Clear Lake thermal anomaly to the regional heat

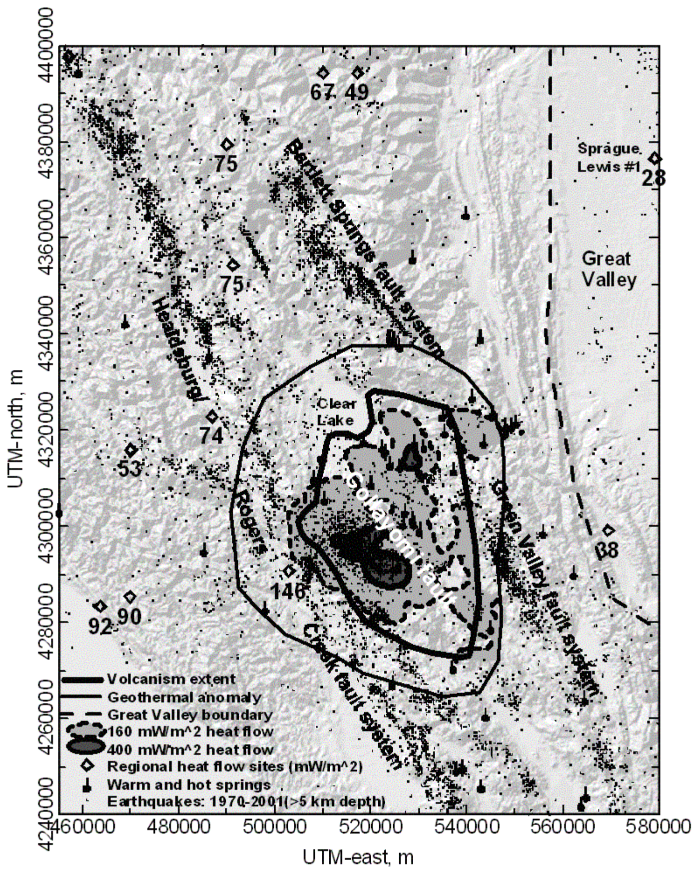

Figure 1.

Regional shaded relief map with topography, earthquake epicenters, major faults, hot springs, regional heat flow points, outline of <2.1 Ma volcanism, contours of anomalous heat flow, and postulated limit of regionally elevated temperatures associated with The Geysers/Clear Lake geothermal area. The 160 and 400 mW/m2 heat flow contours are shown. The outline of the volcanics is from Donnelly-Nolan et al. (1993).

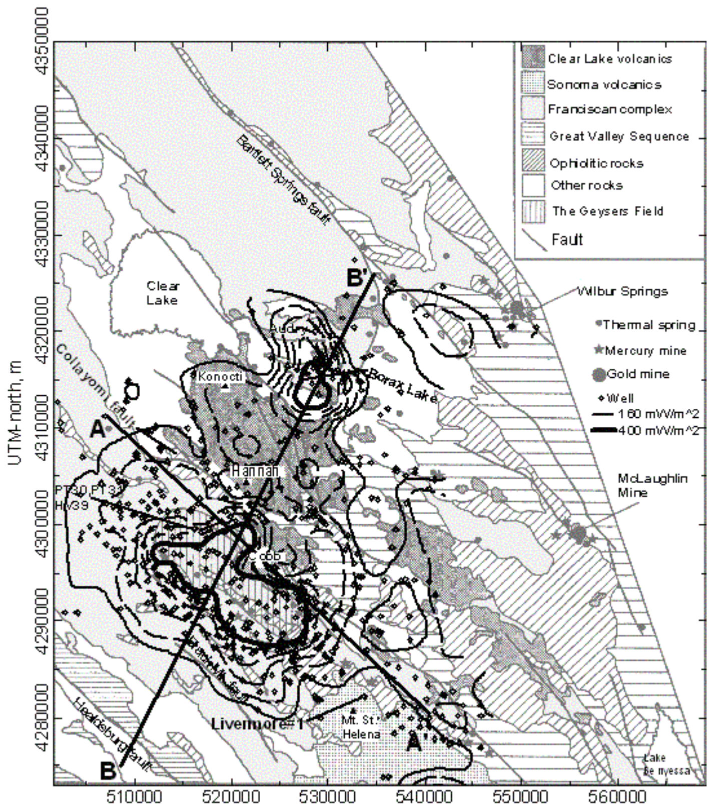

Figure 2.

Generalized geology shown with gradient/heat flow well locations, cross section profiles, and 4 km smoothed heat flow contours. The extent of The Geysers production field closely correlates with the 400 mW/m^2 contour. The limit of the explored area is approximately outlined by the 160 mW/m^2 contour. The geology and base map are adapted from Donnelly-Nolan et al. (1993).

flow of the CRTA is almost completely unknown. The nearest regional point is over 20 km from the area where the heat flow pattern is known from the geothermal exploration drilling. The lowest heat flow there is still over two times the regional heat flow!

Seismic Data

Regionally it has been recognized in the last 10 years that active seismicity occurs along two north-northwest trending zones parallel to the San Andreas (i.e. the Rogers Creek-Healdsburg-Maacama fault zone and the Green Valley-Bartlett Springs fault zone, see Stanley et al., 1998). Approximately 100,000 hypocenter event locations in the vicinity of The Geysers field recorded from 1970 through 2001 were retrieved from the Northern California Data Center and are plotted in Figure 1. The events clearly delineate the major fault zones (the Healdsburg-Rogers Creek fault system and the Bartlett Springs and Green Mountain fault system). In addition the production area shows prominently on the epicenter map due to numerous production related microearthquakes that occur in the immediate vicinity of the field to depths of about 1-3 km (Smith et al., 2000). North and south of The Geysers area there are few earthquakes between the two fault zones. There is also a noticeable lack of seismicity between the Bartlett Springs and Green Valley fault systems east of Clear Lake centered on the Wilbur Springs area. The gap in earthquake epicenters along the Green Valley and Bartlett Springs fault systems could indicate that the region of elevated temperatures extends northeast from the production field beyond this fault zone. Unfortunately, there is very limited well data to constrain the heat flow north and east of Clear Lake.

2. HEAT FLOW DETERMINATIONS

Thermal gradient was the primary geophysical exploration tool used in the development of The Geysers field therefore there are a large number of such wells available. The primary published data sources are Walters and Combs (1992), Thomas (1986), Blackwell et al. (1992), Goff et al. (1993), and Stimac et al. (2001). The data were compiled into a single location file. A data set was constructed consisting of, along with the information listed above: thermal conductivity; terrain corrected thermal gradient; and terrain corrected heat flow.

Since most of the exploration thermal gradient wells are nominally either 90 or 150 m deep, the bedrock geologic unit mapped at the surface will probably be consistent throughout the well. Therefore thermal conductivities of the surface rocks were assumed in the deeper portions of the well if no log was available.

The Geysers has high topographic relief (600 m regionally, 300 m locally). At The Geysers, the wells drilled on the ridge tops typically have corrections that increase the gradients by over 30% of the measured value. So topographic corrections were applied to all of the wells. The accuracy of this procedure is estimated to be ±5%.

3. HEAT FLOW AND GEOTHERMAL GRADIENT DESCRIPTION

Temperature-Depth Curves

Temperature depth curves for several deep wells in and around The Geysers/Clear Lake area are plotted in Figure 3 to demonstrate the deeper thermal conditions. The Sprague-Lewis #1 well, located in the Great Valley (Blackwell et al., 1999), has a heat flow of 28 mW/m^2 (see Figure 1 for the location) typical of the Great Valley but less than 1/2 the 75 mW/m^2 average for the Coast Ranges (Lachenbruch et al., 1980). An example temperature-depth curve for the area of the CRTA is also shown. There are no thermal data from deep wells in the CRTA so the example is plotted assuming a heat flow of 75 mWm^2 and a thermal conductivity of 2.5 W/m/K.

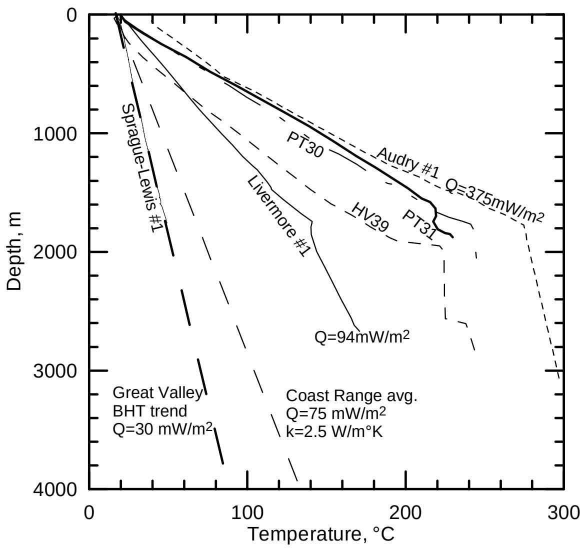

Figure 3. Temperature depth curves for selected deep wells in the vicinity of The Geysers/Clear Lake region. The long dash lines represent the Great Valley and Coast Range average curves.

Three wells on the plot are associated with The Geysers geothermal field (PT-30, PT31, and HV39, Williams et al., 1993) and one is in the Clear Lake volcanic field (Audry #1 at Borax Lake, Beall, 1985). All of these wells reach 200° C at less than 2 km depth. The gradients in the wells that are in The Geysers steam field change abruptly in the wells when the convective system is encountered. The change from high to low gradient marks the point where the wells enter the steam dominated portion of the reservoir. Above the steam reservoir the temperature depth curves of the wells are generally linear with high gradients and so the gradients in even shallow wells can be used to predict the depth to the steam reservoir (Urban and Diment, 1975, Blackwell et al., 1992). The very high temperature in the Audry #1 well is associated with a localized convective system near Borax Lake and the Sulphur Bank Mercury Mine (White and Robertson, 1962).

Outside of The Geysers steam field and the immediate area of the Borax Lake area, but inside the 160 mWm^{-2} contour, deep wells in the Clear Lake region consistently have gradients of about 90 to 100 °C/km and generally linear temperatures-depth curves (Stimac et al., 2001 tabulates gradients from 17 wells over 2 km deep). The heat flow values from these wells are similar to those in the shallow wells and both the values and the shapes of the temperature-depth curves (where available) are consistent with conductive heat transfer. All of the deep wells have anomalously high temperatures relative to the already high Coast Range heat flow, even though several of them are far from the geothermal production. An example plotted in Figure 3, the Livermore #1 well, is about 15 km south of the south end of The Geysers steam field and out of the main thermal anomaly described by Walters and Combs (1992). It has a projected temperature of about 200°C at 3 km and a heat flow of 94 mW/m^2.

Nature of Heat Transfer

Overall an area of over 2500 km^2 has elevated heat flow above the high Coast Range heat flow of about 75 mW/m^2. In spite of the large area, the high thermal manifestations are limited in extent, essentially occurring only in the southern part of The Geysers area and at Borax Lake/Sulphur Bank Mine. The deep wells in the area indicate only minor effects of convective heat transfer although there is very active convection within The Geysers reservoir. The Geysers system is completely isolated from its surroundings as indicated by the very low reservoir pressures (less than the equivalent of 300 m of water at depths of 3,000 m or more (Williamson, 1992). Although there may have been a hydrothermal convective system at early stages of the system (Moore and Gunderson, 1995, Moore et al., 2000) the low permeability caused the system to dry out and become steam dominated (Norton and Hulen, 2001; Brikowski, 2001). Thus in spite of the young volcanism and extensive geothermal system in the area, the heat transfer through the crust outside of the immediate steam system is dominated by conduction.

The mean heat flow over the 2500 km^2 area of the anomaly is about 150 mW/m^2 so the average anomalous heat flow is only about 75 mW/m^2 (100% of the background heat flow) This situation can be contrasted with a caldera system with an active hydrothermal system such as Yellowstone. There the surface area is about the same but the average heat loss is about 2000 mW/m^2 (Fournier et al., 1970), or about 2000% of the background heat flow (Morgan et al., 1977).

The parameter that is used in characterizing the nature of the heat loss in a geothermal system is the nondimensional Nusselt (Nu) number - defined as the ratio of the total heat loss to the conductive heat loss that would occur in the absence of the convective system:

$$Nu = Q_{total} / Q_{conductive} \qquad (1)$$

There is a theoretical and emperically derived relationship between the Nusselt number and the Rayleigh (Ra) number of a convecting fluid system in a uniformily permeable medium given by (Elder, 1965):

$$\log(Nu) = A * \log(Ra) \qquad Ra > 40 \qquad (2)$$

The conductive heat loss can be estimated using as limits conductive cooling of a continuous and instantaneous thermal source. Lachenbruch et al. (1976) point out that the maximum instantaneous heat flow is exactly ½ the continuous heat flow at steady state so the difference associated with these extreme assumptions is only a factor of 2. The only other parameter that needs to be estimated is the depth to the source so that the difference between 4 and 8 km is only another factor of 2. Estimated Nusselt numbers for several large geothermal systems are summarized by Ziagos and Blackwell (1982). These range from 1 in the conductive regime of the Western Cascades (Blackwell et al., 1982) to over 20 for the Yellowstone and Taupo New Zealand systems. Clearly The Geysers steam system at 3 to 2 is as nearly conductive and thus has low permeability compared to most geothermal system examples, consistent with the inference of low permeability associated with steam dominated systems.

4. TWO-DIMENSIONAL THERMAL MODELS

Two-Dimensional Modeling

Two heat flow profiles across the region chosen for comparison are shown in Figure 2. Section A-A' runs NW/SE along the side of the production field and Section B-B' trends SW/NE through the production field and Sulphur Bank. Two dimensional models were used because of the size of the anomaly relative to its depth. This point is more clearly demonstrated in the 3-d modeling section. A profile parallel to section A-A' directly through the center of the production field has the same shape but a much larger amplitude. Figure 4 shows observed and simulated heat flow in The Geysers/Clear Lake area using a series of 2-D conductive magma intrusion models. A wide range of models were run to determine possible end member cases that could generate the heat flow observed at The Geysers. The models were calculated using a 2-d finite difference numerical model with the parameters shown in Table 1. The Geysers region undergoes episodic intrusion phases consisting of multiple small impulses. In the models, single large intrusions are used to represent the cumulative thermal energy input of the many smaller intrusions. Because heat transfer is a diffusive process the present thermal regime represents an average of the past temporal and spatial intrusive activity and this simple approach can be used to represent this integrated response.

Table 1 Thermal Properties of the 2D finite difference numerical models. Surface temperature is 15 °C.

	Thermal Cond. (W/m°K)	Heat Gen. ($\mu W/m^3$)	Initial Intrusion Temp (°C)	Intrusion TC (W/m°K)
Upper Crust (0-14 km)	2.51	1.0	1000	2.30
Lower Crust (14-30 km)	2.30	0.0	1300	2.30

Figure 4 shows the two observed heat flow profiles compared with heat flow profiles calculated from the various models 1 My after intrusion or initiation of intrusion. The felsite intrusive body at The Geysers is dated to be approximately 1 My so that age was chosen for model comparisons. The large peaks of over 300 mW/m^2 in the real data are caused by convection in the steam reservoir. We are only interested in modeling the conductive aspects of the system, matching the lateral extent, and constraining the depth of the heat source. So the heat flow of 300 mW/m^2 was chosen for matching (i.e. assuming a Nu = 2). The cross section plot below the heat flow profiles shows the depth and size of the intrusions used to generate the profiles.

Models 1 through 4 represent the heat source modeled as an upper crustal silicic intrusion, and model 5 represents the heat source modeled by a mid-lower crustal heat source as postulated by Blakely and Stanley (1993) and Stanley et al. (1998). The temperatures for model 5 are generated with a continuously recharging heat source for comparison. In models 1-4 an intrusion temperature of 1000° C was used to represent a 750° to 850° C granitic intrusion with 150° to 250° C additional heat to approximate latent heat (30 to 50 cal/gm). All four upper crustal intrusion models have a common bottom boundary at 10 km but vary in thickness, width, and time pattern of intrusion recurrence.

The simplest model is an instantaneous intrusion with no replenishment (model 4). A single instantaneous intrusion must be much larger than a recurrent or continuously recharged intrusion to generate the same heat flow.

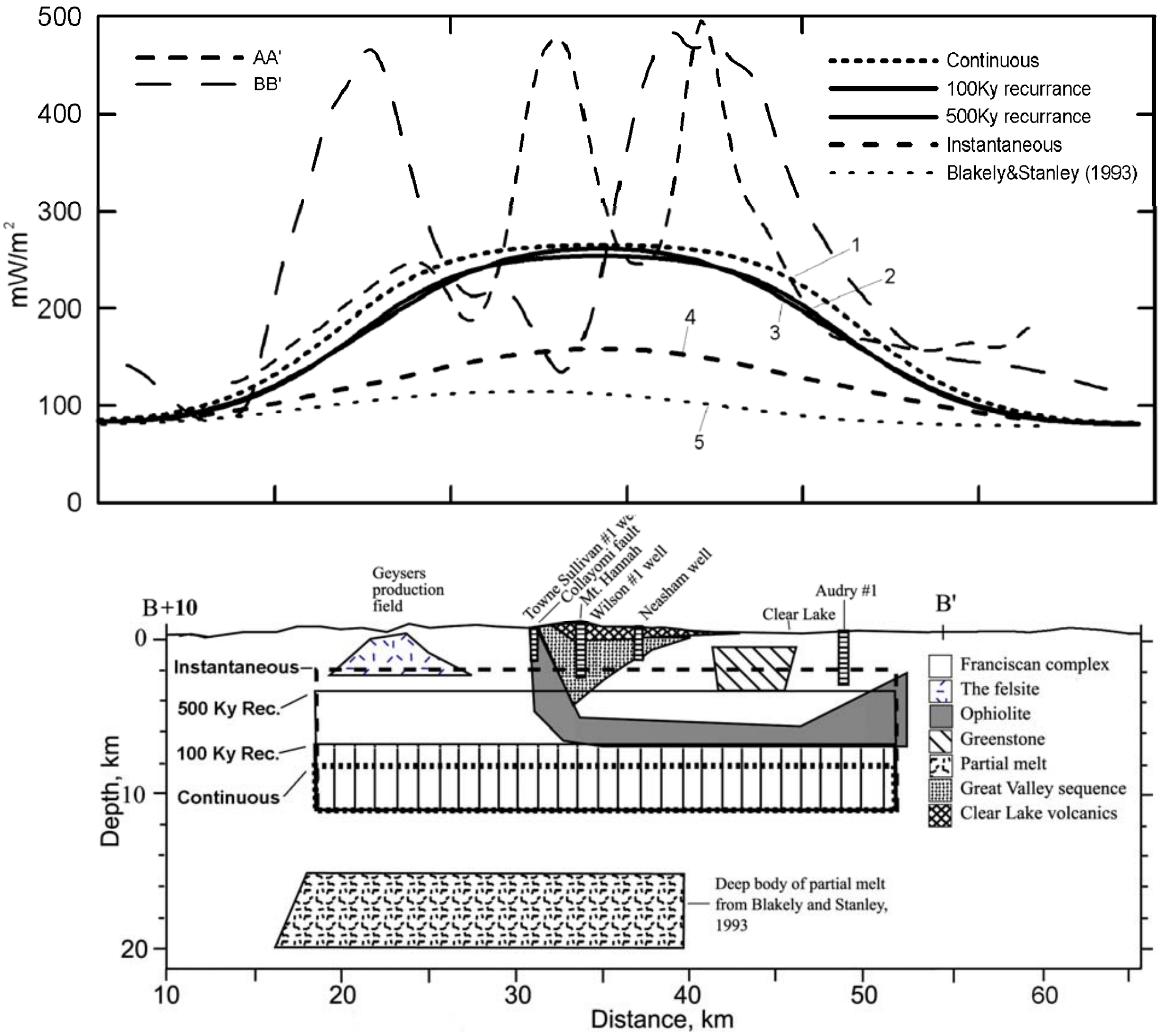

Figure 4. Heat flow profiles from representative models described in the text plotted against heat flow profiles AA' and BB'. Model size was constrained by matching the width and heat flow gradients on the edge of the anomaly for the SW/NE profile (long-dashed line). The models do not attempt to match the peak amplitudes, caused by convection. The reason for using 250 mW/m^2 for the maximum heat flow is discussed in the text. The structure in the section is modified from Blakely and Stanley (1993) by the addition of the upper crustal bodies.

In fact it is not possible to make a single realistic instantaneous body large enough to achieve the heat flow observed in The Geysers. As shown in Figure 4 the maximum heat flow from such a body with a top at 3 km never exceeds 140 mW/m^2. Furthermore the heat flow peaks at about 0.4 Ma after intrusion and the thermal effect is almost completely gone after 1 Ma. Clearly, as has already been pointed out, the Geysers felsite cannot be directly the heat source for the present geothermal system (Stimac et al., 2001; Norton and Hulen, 2001).

As the rate of recharge becomes more regular the top of the body required to generate a peak heat flow of 250 to 300 mW/m^2 at 1 Ma deepens. For a 500,000 y replenishment cycle the top must be at 3 km, for 100,000 y it will be at 8 km and for a continuously replenished chamber it can be at 9 km (in all cases the heat flow is evaluated just before another intrusive episodes). So with this condition the 500,000 y rate is similar to the instantaneous whereas as the 100,000 y model is similar to the continuous one. A continuously recharged intrusion (model 1) could easily generate enough heat at 1 My to fit the observed data (the rise time about 1 My), but a continuous intrusion of this size does not appear to be geologically plausible. Periodic intrusions replenishing the heat source every several 10's to a few 100's of thousand years for at least the last 1+ Ma are more likely. A body, 1 km thicker than the continuous body, with a recurrence interval every 100,000 years (model 2) can produce an almost an identical heat flow anomaly.

The effect of the geothermal system is to increase the heat loss over the equivalent conductive model. That increase is on the order of 100% (see below) for the southwest ½ of the anomaly (The Geysers steam field). So in fact the time constant for cooling is even shorter that for a purely conductive model. This situation was modeled in a crude way by increasing the thermal conductivity above the intrusive mass by 100% for the continuous model (4). In this case a heat flow of almost 400 mW/m^2 is generated by the continuous model, but the peak heat flow requires a 100% longer time to be reached (2 Ma instead of 1Ma). The equivalent model 3a (the 500,000 y recurrence) does not reach equilibrium after 10 Ma and so clearly is not a viable model if the rate of convective heat transfer has remained effective over the history of the magmatic event. The present heat loss rate is about equivalent to 0.005 km^3 of cooled magma per year. If the system has been operating for 2 Ma then a total intrusive volume of predominantly silicic magma of about 10,000 km^3 has been emplaced, i.e. a body about 6 km thick if it is 40 km square in surface area.

The bottom of the heat source is not resolved by this modeling. The thermal field in the shallow subsurface is not sensitive to this parameter. It could be a model like the one of Stimac et al. (2001) or could be continuous with a deeper body of the type postulated by Blakely and Stanley (1993) and Stanley and Blakeley (1993). Figure 4 shows the magma chambers for models 1 through 4 at their modeled depth and thickness superimposed on the structural model of Blakely and Stanley (1993). It is clear that the deep body of this sort is not a viable model for the observed thermal regime. Even if it is modeled as a continuous body the thermal effect in the 1 to 3 km depth range is insignificant. This discussion is expanded in the concluding section.

5. THREE-DIMENSIONAL MODEL

The availability of extremely dense and deep information on the thermal regime is relatively unique. To more full take advantage of this data set we carried out an inverse three dimensional interpretation of the upper crustal thermal regime. The modeling is based on the observation demonstrated above and in the papers cited that the thermal regime is basically conductive outside of and below the steam field. In this case the surface heat flow pattern and the deep measured temperatures constrain the distribution of temperature at depth. The assumption is made in the modeling described here that the thermal conductivity is constant. This assumption is a reasonable approximation since the thermal conductivity of most crustal materials is within a factor of ±25% or less at temperatures of over 300°C. The temperature pattern is retrieved by inverse modeling using the downward continuation technique described by Brott et al. (1981). The specific configuration used assumes that the temperature dipoles were turned on at 1 Ma and have been at a fixed temperature since that time. So the medium is heating up and the solution is similar to the two-dimensional continuous assumption in the preceding section. The solution is not valid to the extent that significant intrusion occurs above 6 km as all sources of heat are assumed to be below that depth in the area of temperature calculation. The input gradients were assumed to be on a plane surface that is the mean elevation of the area (600 m) so that elevation is the zero level for the temperature maps at depth.

Because of the nature of the inverse process to obtain a stable solution only longer wavelength components of the thermal field are needed. So the input heat flow data at a 1 km interval were smoothed by a 4 point running average to remove the shallow "noise" before the inversion procedure was applied. The input gradient map was also hand edited to remove an approximation of the convective component of the gradient in the vicinity of The Geysers field that cannot be accurately continued downward based on the assumption of purely conductive heat flow.

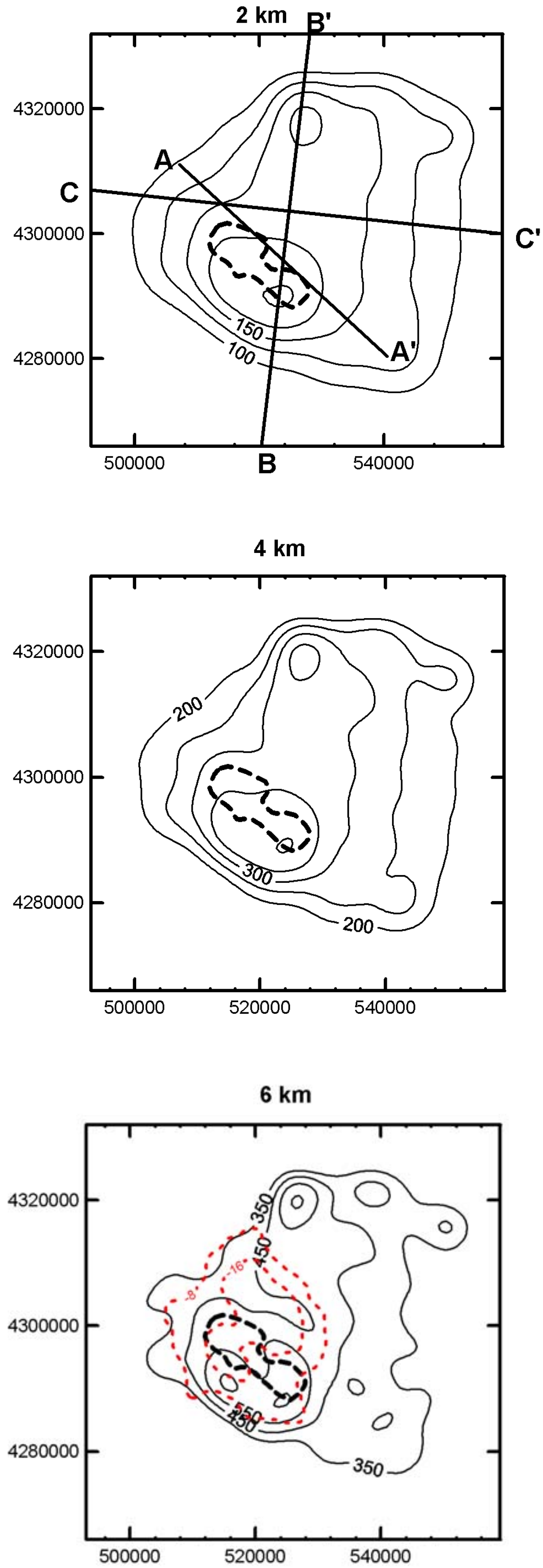

Figure 5. Temperature maps at intervals of 2 km from 2 to 6 km depth based on the downward continuation interpretation. The Geysers steam field is shown.

Figure 5 shows a series of temperature maps calculated at 2 km intervals from 2 to 6 km depth. The results of the continuation show a very large hot region in the upper crust beneath The Geysers/Clear Lake region centered on, but by no means confined to, the area of the producing field and the Clear Lake volcanic field. At depths of 4 to 6 km the area of anomalous temperature is about 30 km in diameter. Thus, even discounting the high heat flow of the geothermal field does not affect the conclusion that there is a large, young, shallow plutonic body underlying the whole region. The equivalent body size is about 20 x 20 km. Smaller separated bodies on the order of 5 km^2 will not produce this magnitude of anomaly because of the short thermal time constants and small heat contents of such bodies. This deep result is not affected by the treatment of the effect of the steam field. The thermal regime is clearly responding to a larger thermal mass at depth. The thermal anomaly is so large that it is still almost 1-d even at depths of 5 to 6 km as indicated by the generally smooth lateral decrease of the temperatures. This is in spite of the fact that the edge of the anomaly is conservatively drawn in the absence of thermal data at near regional distances. The earthquake data are permissive of a much larger body at a depth greater than 6 km.

Even after smoothing and removal of the postulated convective effect the highest temperatures still are associated with the location of the producing field shown by the heavier line. It is apparent from the continuation to 2 km depth that there is a very large region of 200°+ temperature resource for possible production even discounting the convective effects in the steam reservoir. By 6 km depth, calculated temperatures below the production field could be above 600° C and are thus close to the melting point of upper crustal rock. The high heat flow peak at Sulphur Bank also shows peaked temperatures at depth, but is really too small to be properly resolved on this 1 km spaced grid.

The edges of the anomaly are smooth and it tapers off gradually at shallow depths but significant topography appears on the 6 km depth map. One of the characteristics of the inverse approach is that the sharpness of the field increases with depth as the sources are approached. The 6 km temperatures show several locations where the contours become very closely spaced implying that the depth of the apparent source has been reached (south of the steam field and in the NW corner of the anomaly).

Performing the downward continuation on the well constrained gradient information at The Geysers is a very powerful tool because it creates a 3D temperature model to depths that cannot be economically reached by drilling. With this map we can estimate the depth, size, and shape of the subsurface temperature field and its causative heat source.

A section of the continuation results to a depth of 6 km in comparison to the 2-d results is shown in Figure 6. The temperatures for the 100,000 y recurrent 2-d models are shown. The agreement is quite close in general, but the 3-d continued temperatures show more structure than the simple 2-d geometry produces. The N-S section (section B-B', Figure 5) shows lower temperatures in the center of the anomaly (about 450°C instead of about 600°C). An E-W section (section C-C', Figure 5) through the center of the anomaly emphasizes this difference showing the lower temperatures compared to the northern and southern areas. One implication is that the continuation solution is identifying two source areas that separate at depth implying two centers of magmatism. A second implication is that the thermal data along the Collayomi fault are affected by groundwater effects ad do not reflect the deep thermal conditions as well as the rest of the thermal data set.

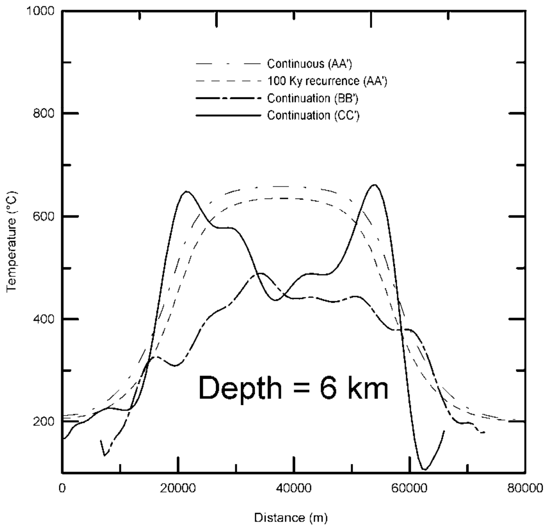

Figure 6. Comparison of the temperatures at 6 km depth from the continuous and 100 ky recurrence 2-d models and the downward continued temperatures

6. DISCUSSION AND CONCLUSIONS

The regional geophysics has been investigated using many techniques with the earlier studies being summarized by Majer et al. (1992) and with more recent studies summarized by Stanley and Blakely (1995) and Stanley et al. (1998). The most interesting result is the gravity anomaly. The residual gravity anomaly pattern shows a large negative anomaly with a close geographic correspondence to the thermal anomaly (Isherwood, 1981, Majer et al., 1991). Two contours of the gravity anomaly are shown on the 6 km continuation temperatures in Figure 5. There is a close correspondence with the 6 km temperature of over 450 °C. Temperature (thermal expansion) alone cannot explain the amount of the gravity anomaly. However, Stanley et al. (1998) argue that the density contrasts that cause the gravity anomaly are related to upper crustal structure and are not directly related to the thermal anomaly. Stanley et al. (1998) were not able to locate a crustal velocity anomaly associated with the area of high heat flow. They concluded that "small, young, intrusive bodies that were injected along a northeast trend from The Geysers to Clear Lake probably control the thermal regime" and relegated the long term intrusive effects to the lower crust. The modeling in this paper shows that their conclusion is not a satisfactory thermal model unless extensive hydrothermal convection penetrates to depths of 15 km or more on a crust that appears to behave in a ductile manner below about 6 km.

The Geysers heat flow anomaly is much larger than the producing steam field. The broad extent of the anomaly provides promise of greatly increased energy production outside of the existing production field by applying other techniques such as EGS. Downward continuation of heat flow/gradient data indicates that the effective top of the heat source is near 6 km depth and requires temperatures only achievable by melts in the mid to shallow crust agreeing with the gravity findings of Isherwood (1981).

Thermal models show that a single intrusion 1 Ma cannot explain the high heat flow observed presently and intrusions every 500,000 years (model 3) would require a very large volume of melt injection unless such an event had happened within the last 100,000 to 200,000 y. This young large scale activity is not supported by surface evidence. The equivalent model 3a (the 500,000 y recurrence) that matches the actual heat loss (both conductive and convective) does not even reach equilibrium after 10 Ma and so clearly is not a viable model if the rate of convective heat transfer has remained effective over the history of the magmatic event. Intrusive episode intervals are therefore required to be (much) less than 500,000 years to match the heat flow with a reasonable volume of melt. An episodic intrusion cycle would allow for periods of time without melts in the crust, but the crust must remain near the melting temperature in the 5 to 10 km depth range or the observed widespread thermal effects would not be produced. The felsite intrusive body indicates that the magmas can be very shallow, but a body of the observed felsite size is insignificant to the long term observed thermal regime. The present heat loss rate is about equivalent to 0.005 km^3 of cooled magma per year. If the system has been operating for 2 Ma then a total intrusive volume of predominantly silicic magma of about 10,000 km^3 has been emplaced, i.e. a body about 6 km thick if it is 40 km square in surface area.

Based on drilling, the major magma chambers do not exist in the upper 3 km, yet bodies below about 10 km cannot produce high enough upper crustal temperatures to match the observations even with a continuously replenished regional scale intrusion. Thus the center of magmatism must be in the upper crust. The inability of the seismic observations to locate a velocity anomaly and electrical techniques to find a resistivity anomaly (Stanley et al., 1998) does not mean that a magma chamber in the thermal and geological sense in the upper crust does not underlie this area. The gravity anomaly does tend to agree with the location of the crustal heat source required by the thermal modeling. We conclude from this analysis that gravity and thermal geophysics are more effective at locating and characterizing many types of upper crustal magma chambers than are seismic and electrical studies.

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