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CONVECTING HYDROTHERMAL SYSTEM

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INVERSION APPROACH FOR THERMAL DATA FROM A CONVECTING HYDROTHERMAL SYSTEM

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ABSTRACT

The Salton Sea geothermal system (California, U.S.A.) is a hot, hypersaline convecting system driven by intrusions into a sediment-smothered rift system north of the Gulf of California. In this paper we describe efforts to invert thermal data from 13 deep geothermal wells, and from additional shallow heat-flow holes, in order to determine the age and total flow rate of the hydrothermal system.

Conventional forward modeling approaches involve presuming the initial conditions, such as the temperature and permeability distributions. The evolution of the thermal field and fluid flow pattern is calculated using the equations of continuity, Darcy's Law, energy balance, and an equation of state for the fluid. For several reasons this approach is not useful for inverting the observed temperatures at the Salton Sea field: 1) The observed data appear to be entirely within a zone of relatively uniform horizontal flow, and do not sample the entire flow field. For example, none of the wells studied shows a significant temperature reversal which might occur at greater depths. 2) Dramatically different starting models produce similar flow patterns in the upper (sampled) part of the system. Consequently, many of the parameters needed to specify the complete model cannot be determined from the available data. 3) It is difficult to do parameter studies with complete numerical models, which require considerable computer time.

We have inverted the data for a very restrictive model: single-phase, horizontal flow along prescribed flowlines in a single aquifer bounded by an impermeable cap and base. With simplifying assumptions, the results are shown to depend on only two parameters, the system age, and the aquifer/cap thickness ratio. The surface gradient and temperature distribution within the cap are calculated analytically for all possible parameter values. Those parameters producing temperatures that agree with observations are identified, and the range of acceptable parameters is

reduced by conclusions drawn from other geophysical data. The cap thickness is inferred to be 500m from thermal and lithologic data from the wells. The aquifer thickness is limited to less than 2500m by seismic, resistivity and magnetic data. We conclude that if this model is valid, the system age is constrained between 3000 and 20,000 years.

INTRODUCTION

Thermal measurements provide the most direct evidence about the location and nature of heat sources in the upper crust. Unfortunately, extrapolation of near-surface heat flow data through a hydrothermal system where convecting fluid carries heat is very unreliable unless the convecting system is well understood. In this paper, we review the application of two approaches for inverting the thermal data from the Salton Sea Geothermal Field in Southern California (Figure 1) and show that a relatively simple analytical model can provide useful estimates that constrain the age and evolution of a hydrothermal system in which lateral fluid flow is dominant.

The Salton Sea Geothermal Field is an active, hypersaline, fluid dominated system with temperatures that reach 360°C at a depth of 2.5 kilometers in the center of the field (Helgeson, 1968). The data available for the interpretation includes temperature versus depth profiles to 2.5 km in 13 wells, surface heat flow, surface geophysical surveys, and detailed geologic information on the sedimentary section. (See Younker, et al., 1982 for a summary of the available data).

We first briefly review the geological and geophysical characteristics of the Salton Sea Field with an emphasis on the thermal characteristics of the field. We then apply a coupled heat and mass transfer numerical model in which two dimensional flow about an impermeable magma body intruded into porous sediments is calculated (Lau 1980a, 1980b). General features of the thermal field can be matched by model calculations, however, a variety of reasons preclude using this approach to rigorously infer additional constraints on the hydrothermal system. A simple analytical model which replaces factors controlling the flow with the assumption of uniform flow can also match thermal observations for the known part of the field. The simplicity of the model allows the entire range of parameters to

be efficiently evaluated. Adding geophysical constraints that define the geometry of the caprock and reservoir enables estimates of the system age and mass flow rates to be calculated.

SALTON SEA GEOTHERMAL FIELD SETTING AND CHARACTERISTICS

The Salton Trough can be essentially viewed as an area of very high regional heat flow produced by complicated crustal rifting modified locally by shallow crustal intrusions and associated hydrothermal circulation (Lomnitz et al., 1970; Elders et al., 1972; Elders and Biehler, 1975; Fuis et al., 1982). The largest and hottest of these geothermal fields is the Salton Sea Geothermal Field which has large geophysical anomalies perhaps reflecting partly cooled igneous intrusions at shallow depths (Elders et al., 1972; Younker et al., 1982). The sedimentary sequence in the region consists of an upper lacustrine sequence of clay, silt, and evaporites underlain by a thick sequence of sandstones and shales (Muffler and White, 1969; Randall, 1974).

The upper caprock represents a physical barrier to fluid flow such that any upwelling hot fluids are diverted laterally, thereby producing a significant horizontal flow component in the shallow parts of the field (Kasameyer and Younker, 1978). This horizontal component is further enhanced by permeability anisotropy in the deltaic sequence and vertical fluid salinity gradients which tend to preclude large-scale vertical fluid movement (Younker, et al., 1982).

Two features of the temperature field in the Salton Sea Geothermal Field put very strong constraints on models of the development of the hydrothermal system (Younker et al., 1982). First, uniform, steady-state heat-flow is observed in a 500 m thick thermal cap over an area of 30-40 km². This observation indicates that the fluid flow patterns and rate of heat delivery to the thermal cap in this area have not changed for at least the time required for the cap to come to equilibrium.

Second, the periphery of the high heat flow zone is abrupt, and the thermal gradient in the cap increases significantly with depth as the hydrothermal zone is approached. These observations indicate that heat has been delivered to the periphery for a much shorter time than is required for conduction in the cap to spread the boundary or to come to steady-state equilibrium.

Temperature profiles showing these patterns are illustrated in Figure 2-4 (see Younker, et al., 1982, Figures 12 and 13 for the complete data). Figure 2 shows the interpreted regions in the geothermal field. The central part of the field has a high gradient in the cap and uniform heat flow over a broad area. The transition zone is a narrow band and has concave up temperature in the cap. Representative temperature profiles are shown in Figure 3 for the central part of the field and the transition region. Figure 4 shows normalized temperature gradient in the cap versus distance from the center of the field. The rapid transition to lower gradients is apparent on this plot. These characteristics of the temperature field in the Salton Sea System provide the basis for the inversion and interpretation to follow.

INVERSION APPROACH - COUPLED MODELS

The usual method for modeling geothermal systems is to presume a set of known initial conditions such as temperature and permeability and then calculate the resulting fluid flow and heat transfer patterns. These simple heat/mass transfer models can be used to calculate temperatures and the resulting thermal field can be compared with observations such as those discussed above. Lau (1980a) has developed such a model. Critical assumptions in his formulation include two-dimensional flow, anisotropic permeability, impermeable cap and intrusion, single phase, and a simple equation of state.

The resulting idealized model of the geothermal reservoir with a dike intrusion is shown in Figure 5. The cooling of the magmatic intrusion due to natural convection is considered by taking into account the effects of overlying cap rock and different horizontal and vertical permeability, within the reservoir. The caprock thickness is variable. The evolution of the thermal field and fluid flow patterns is calculated using equations of continuity, Darcy's Law, Energy Balance and an equation of state for single-phase flow. The flow field (stream function, velocity) is initialized to zero everywhere in the flow region. The temperature field is zero everywhere except in the region of the intrusive dike. The surface boundary condition is constant temperature. Boundary conditions are indicated in Figure 5. The caprock is impermeable and conductive. The energy equation is solved numerically by the Alternating Direction Implicit (ADI) method, and the flow field equation by the Gauss-Seidel iteration method. The region is divided into a uniform mesh. Parameters needed to specify a calculation include the location and height of the dike, thickness of the caprock and reservoir, Rayleigh number, vertical to horizontal permeability ratio, thermal properties of the caprock and reservoir, and the maximum temperature contrast between the intrusion and the surrounding reservoir (Table 1). The numerical procedure used can be described briefly as follows: (1) Initial data values are set to conform to the initial conditions. (2) The temperature field solutions are obtained for the first time step. (3) The stream function equation is solved by the Gauss-Seidel interaction method. The iteration cycle is terminated when the maximum change in stream function values is less than 10^{-5} during two successive iteration cycles. (4) Velocity components are calculated. (5) Temperature field solutions are obtained for the next time step and the procedure repeats until the maximum time step is reached.

An example of this type of calculation is shown in Figure 6. In that example a two-dimensional intrusion has been placed into an isothermal homogeneous layer with horizontal permeability greater than vertical permeability. The caprock is of uniform thickness. The evolution of the thermal field and fluid flow patterns is shown for seven time steps. The results are useful because they illustrate many of the processes which occur when a static system is perturbed by a hot intrusion. These processes include development of buoyancy of heated fluid above and beside the intrusion, transition of the heat flow from convective to conductive at the aquifer/cap boundary, a broad region of relatively horizontal flow away from the center of the intrusion pushing the isotherms into a "mushroom" shape, and a diffuse zone of recharge beyond and beneath the zone of lateral spreading.

In addition, the calculations produce some of the features of the Salton Sea Geothermal Field described earlier. Figure 7 shows an example of the calculated evolution of the surface gradient with time. It is noted that for a restricted range of times early in the evolution of the system, a relatively sharp dropoff of surface heat flow is developed similar to that shown in Figure 4. At later times the heat flow anomaly decays over a long distance.

This modeling approach is very useful for solving the "forward" problem: i.e., given initial conditions and a specified intrusion, what is the resulting thermal field? For several reasons it is not so useful for "inverting" the observed temperatures from the SSGF to determine the initial conditions.

First, the observed data usually sample only a small part of the hydrothermal system. The temperature increases with depth monotonically in every profile published for the SSGF (Helgeson, 1968; Younker, et al., 1982). Because there is little economic incentive for drilling through zones where temperature decreases with depth, this feature is common to many areas explored for commercial purposes. Given this constraint, Figure 8 illustrates that the flow system is inadequately sampled. Streamlines and temperature-depth curves are shown for a

particular set of parameters. The temperature curves increase monotonically only within the cap, the area directly above the intrusion and the upper part of the zone of rapid, uniform horizontal flow. At the SSGF, there are no profiles from the central core of the flow field or from the area of recharge. Consequently, inversion of the data can only determine factors which influence the temperature and flow field in the upper part of the hydrothermal system.

Second, dramatically different starting models produce very similar flow patterns in this upper part of the system. Figure 9 shows flow vectors for different geologic models. Each of these models produces horizontal, nearly uniform amplitude, flow over a broad area just beneath the cap. Figure 9A shows that if the permeability ratio is small, as has been detected at the SSGF, then the zone of uniform horizontal flow could extend over 90% of the width of the hydrothermal system. The effect of changing parameters can be evaluated by comparing plots in Figure 9. Plot 9C shows that reducing the height of the intrusion reduces slightly the range over which the flow just beneath the cap is horizontal. The parameters for plot 9D are identical to 9A, except the anisotropy has been reduced by a factor of 3. The width of the convection cell is reduced somewhat, and the fraction where flow is horizontal is slightly reduced. Still, in the area not directly above the intrusion, the flow under the cap is predominately horizontal and uniform. Increasing the cap thickness by a factor of three also produces similarly small effects (Figures 9B and 9D). Because many sets of parameters produce the same flow, the parameters needed to specify the complete model cannot be uniquely determined from the available data. By applying a linearized inversion approach to this problem, it would be possible to identify the combinations of parameters which could be determined from the data set. This approach is not practical, however, because of the accuracy limitations and costs of this modeling method.

Third, the coupled 2-D models require enough computer time that using them to do a complete parameter study is impractical. For example, the model of Lau (1980a) requires 1.1 minutes of CDC 7600 CPU time to calculate the flow and temperature field after 10 time steps for a single set of parameters. Models with enough elements to calculate the heat flow accurately would require more time. A parameter study where the 8 or 9 parameters required to specify the problem are varied independently would be cumbersome and unproductive.

In addition, there are considerable differences in scale between the system being modeled and the available data. The calculations were made on a uniform grid with twenty elements from top to bottom. Geologic information indicates that the hydrothermal system could have a height of 6 to 10 kilometers. On the other hand, measurements indicate that one of the most important factors is curvature of the temperature-depth profiles within the 500m thick cap. Normally, there are not enough grid values within the cap, and the calculated heat flow is the average over the cap thickness. A much thicker cap was included in the calculations for Figure 8, in order to indicate that the curvature can be seen in areas where hot fluid has recently flowed under the cap rock. In order to accurately calculate the surface heat flow, a variable grid spacing would have to be incorporated, with many more subdivisions within the cap.

While the numerical model is not very suitable for inverting the data, it does provide insights useful for simplifying the problem. One observation from the numerical modeling is that once the flow field is established, it changes slowly compared to the evolution of the temperature field. The calculated flow fields in Figure 6 illustrate this property very well. Except in the vicinity of the corner of the intrusion, there is very little change in the flow field once the convection cell is initiated. On the other hand, Figure 10 shows an example where parameters are chosen to allow substantial changes in the flow system. Even in this case, the

changes in the flow field beneath the cap are small except directly above the intrusion. These results suggest that we could reduce the computational complexity by modeling the area where temperature field is observed with an analytical model assuming a fixed fluid flow pattern with only lateral flow. In the next section, we describe an uncoupled analytical model which captures the essential features of the flow field and is efficient enough to be used to invert the thermal data from the field.

INVERSION APPROACH - ANALYTICAL MODEL

By adding some additional simplifying assumptions, it is possible to develop an analytical model which describes the essential characteristics of the thermal and flow field in the area where temperature observations are available and can be used to invert the data. In particular, we replace factors controlling flow with the assumption of uniform lateral flow. Only that part of the system where flow is horizontal is modeled (Figure 11), an impermeable basement is assumed and the temperature gradient in the aquifer is ignored. Details of the model are given in Kasameyer (et al., 1983).

Ignoring changes in the caprock and reservoir thickness through the field, the system is modeled as a single aquifer bounded above and below by regions of conductive heat transfer. Hot water is injected into the aquifer to model the heat put into the system by the intrusions. This approach is similar to the method described by Eckstein (1983). With these simplifying assumptions, analytical calculations are made of the surface gradient, temperature distribution in the cap and temperature distribution along a flowline for all possible aquifer-cap thickness ratios and system ages (Kasameyer, et al., 1983). It was shown that this model can produce the rapid transition between high uniform heat flow over a broad area and an increasing temperature gradient in the cap in the transition region, two notable features of the Salton Sea field. The calculated curves for a given flow rate depend

on only two free parameters, essentially the age and the ratio of cap thickness to reservoir thickness. Thus, it is possible to rigorously and efficiently compare model results with data from the field. In contrast to the numerical method described earlier, the analytical method can calculate the heat flow and temperature profile within the cap accurately at 30 locations for ten different times for 400 sets of geometrical parameters in .019 min of CDC 7600 time, an improvement of a factor of 20,000 over the coupled model. Neither program was optimized to run efficiently, but it is clear that the analytical, uncoupled program runs much faster. The age of the system and system flow rates have been estimated by minimizing the variance between the observed surface temperature gradient data and the model calculations. A contour plot of the variance, defined as the sum of squares of the difference between observed and calculated gradients, is shown in Figure 12, taken from Kasameyer, et al., 1983. Using the contour plot to determine acceptable parameters and adding geophysical constraints on aquifer thickness, the age of the system has been estimated to be between 3,000 and 20,000 years (Kasameyer, et al., 1983). Similarly, mass flow rates ranging between 10 and 30 millions of cubic meters per year have also been estimated. This number is significantly higher than estimates of regional groundwater recharge and may suggest substantial deep circulation.

CONCLUSIONS

Coupled heat and mass transfer numerical calculations are very useful for solving the forward problem of modeling geothermal systems: i.e., given initial conditions and a specified intrusion, what is the resulting thermal and flow fields. For several reasons these types of calculations are not very useful for inverting the observed temperature distribution to determine initial conditions, and to ascertain field parameters. Some of the reasons for this include, (1) limited data,

(2) fundamental non-uniqueness, and (3) cost and accuracy limitations. These calculations, however, do illustrate that a wide variety of parameters produce horizontal flow in the shallow samples parts of the geothermal system. They also show that there is little change with time in the flow patterns in this region as the system evolves.

Coupling these insights gained from the numerical modeling with a generalized horizontal flow model inferred from the spatial pattern of geophysical anomalies and thermal characteristics provides the basis for developing a simplified analytical model for the system. In that model, the factors controlling the flow patterns are replaced with the assumption of uniform horizontal flow in a reservoir between two conductive regions. The simplicity of the model makes it possible to determine the entire range of parameters that provide solutions which match the thermal data from the field and infer useful information about the hydrothermal system evolution.

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FIGURE CAPTIONS

Figure 1.

Location of the Salton Sea Geothermal Field and nearby faults in the Imperial Valley (modified from Elders et al., 1972). Basement rocks are indicated by the stippled pattern.

Figure 2.

Interpreted regions within the Salton Sea Geothermal Field. Central part of the field is characterized by broad region of moderately high uniform heat flow in the upper few hundred meters and a nearby isothermal zone at depth. The transition region is characterized by relatively low heat flow near the surface, but the temperature gradient increases with depth. The outer region labeled regional heat flow is characterized by relatively low heat flow. See Younker et al., (1982) Figure 13 for the actual data upon which the interpretation is made. Representative temperature profiles from the central part of the field and the transition region are shown in Figure 3.

Figure 3.

Temperature profiles from the transition region and the central part of the field.

Figure 4.

Surface gradient plotted against a dimensionless distance parameter. Distance is measured from an inferred center of the field assuming a radial geometry. The distance is normalized by the thermal cap thickness (Z_0) interpreted from thermal profiles to be 500 meters in the central part of the field. The rapid transition from a uniform high gradient region in the center of the field to a uniform low gradient region is readily apparent on the plot. A regional gradient of $0.11\text{ }^{\circ}\text{C/m}$ is subtracted from the data.

Figure 5.

Idealized model of a geothermal reservoir with a dike intrusion and a variable thickness caprock (from Lau 1980a).

Figure 6.

Evolution of streamlines and thermal field, calculated using the computer code of Lau (1980a). The model geometry is shown in the upper left hand corner. The light contours are streamlines. The heavy contours are temperature contours of 10, 30, 50, 70, and 90 percent of the intrusion temperature. The numbers indicate the dimensionless time t' . For this example, $Ra=200$ and $X=0.2$. In this and all succeeding figures, there is no vertical exaggeration.

Figure 7.

Evolution of the surface gradient as a function of distance from the center of a cooling pluton.

Figure 8.

Temperature-depth profiles. Dimensionless temperature-depth profiles calculated using coupled model of Lau (1980a) are shown for six different locations within the hydrothermal system. Streamlines are superimposed to illustrate the relationship between the flow field and the shape of the temperature profiles. A uniform thick cap and tall intrusion, indicated by symbols, were assumed for this calculation. $Ra=800$ and $X=0.2$.

Figure 9.

Flow vectors for different models calculated using the coupled model of Lau (1980a). The direction of and relative magnitude of the flow at each grid point is indicated by the arrows. Model A has a tall intrusion, thick cap and anisotropy ($\chi=0.166$). B has a thicker cap and less anisotropy ($\chi=0.50$). C has a shorter intrusion than A. The geometry of D is similar to A, but the anisotropy is lower ($\chi=0.50$).

Figure 10.

Streamlines calculated for a deep intrusion and a high Rayleigh number, using the coupled model of Lau (1980a). Anisotropy was low ($\chi=0.5$).

Figure 11.

Cross sections of dimensionless temperature (A) and flow velocity (B) for a calculation of circulation resulting from intrusion of a pluton into an anisotropically permeable medium. In Figure 1a, the real temperature is found by multiplying θ by 700°C . The shaded region is the area of relatively uniform horizontal flow and it is the area modeled in the analytical approach.

Figure 12.

Model variance (sum of square of differences between the modeled thermal gradients and the observed) contoured on a plot of $\log t'$ versus $\log p$. Geophysical data on thermal cap and aquifer thickness constrain values of p to be between 3 and 9. System age since flow started is contoured across the plot (from Kasameyer, et al., 1983).

TABLE I

Parameters and symbols for the coupled model of Lau (1980a) and the uncoupled analytical model

Coupled Model Parameters

Ra	Rayleigh Number = $\frac{\rho_0 B g K_y H \Delta T}{\mu \alpha_m}$
g	gravitational acceleration
z_0	cap thickness
H	reservoir thickness
λ_{cap}	thermal conductivity of the cap rock
ΔT	maximum temperature referenced to T_0
$(\rho c)_m$	heat capacity of porous medium
$(\rho c)_f$	heat capacity of fluid
K_x	permeability in x direction
K_y	permeability in y direction
ϕ	porosity of reservoir
β	thermal expansion coefficient
α_m	thermal diffusivity of fluid porous medium
x	permeability ratio K_y/K_x
ρ_0	density fo fluid at $T=T_0$

Uncoupled Analytical Model Parameters

P	Heat Content Ratio = $\frac{H}{z_0} \left[(1-\phi) + \frac{(\rho c)_f}{(\rho c)_m} \phi \right]$
t'	Dimensionless time = $\frac{\lambda_{cap}}{H z_0 (\rho c)_f \phi} t$

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Figure 1.

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Figure 2.

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Figure 3.

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Figure 4.

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 Figure 5.

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Figure 7.

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Figure 12.