REDISTRIBUTION OF TERRESTRIAL HEAT FLOW BY DEEP CIRCULATING METEORIC WATERS RECHARGING LOW TEMPERATURE GEOTHERMAL SYSTEMS

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INTRODUCTION

It is well known from isotopic studies (Craig, 1963) that almost all fluids discharged by geothermal systems originate from infiltrating meteoric waters. This implies that meteoric waters move at various levels towards a geothermal reservoir where hot fluids are discharged at the surface. Such a simple circulation model implies that some redistribution of terrestrial heat should occur since some heat will be transferred laterally from the recharge area into the reservoir.

For high temperature systems, fluid movement in the recharge area causes some cooling, which is indicated by low apparent heat flow and which has been observed away from high temperature systems in the Taupo Volcanic Zone in New Zealand (Studt and Thompson, 1969), and also in Japan; for example, in Hokkaido (Yuhara, 1973). For low temperature systems, regional transfer of heat by deep secular convection might constitute the only heat input, as has been postulated for some low temperature systems in the North Island of New Zealand (Siswojo et al., 1985) and in the U.S.A. (Reed,1983).

Very little has been done to asses the redistribution of crustal heat in recharge areas of geothermal systems since most model studies have been concerned with modelling the fluids flow inside geothermal reservoirs starting with a constant heat input at an inferred base of the reservoir (for example, Kassoy and Zeib, 1978). Recently, attempts have been made to model fluid flow patterns of low temperature systems which not only consider flow beneath the discharge area but also heat and mass transfer for the whole recharge area down to crustal depths of 5 to 10 km. The deep temperature field beneath a sedimentary trough underlain by a basement aquifer in Switzerland has been modelled by numerical simulation to explain high heat flow anomaly near the margin of the trough (Rybach et al.,1987). Numerical simulation has also been used to model apparent high and low heat flow anomalies over an extensive basement aquifer system in China (Hochstein and Yang Zhongke, 1988). However, no attempt has yet been made to simulate the regional heat transfer in the recharge area of the most common type of low temperature geothermal systems, namely, the fracture zone system, where heat is swept by deep circulating meteoric waters towards a deep-reaching, highly permeable fracture zone(or intersection of fracture zones) in which thermal fluids ascend slowly to the surface. In this study the results of numerical modelling of two fracture zone systems are described: the Waiwera system in New Zealand and the Fuzhou system in China. The study allows a quantitative assesment of the redistribution of terrestrial heat for both systems. Reservoir characteristics of both systems have been described recently (Hochstein,1988).

In the following we use the term "terrestrial heat flow" to describe the undisturbed conductive heat flow which would be observed outside the systems in the absence of any fluid flow, and below the level where no fluids move. The disturbed heat flow in the recharge or discharge areas will be referred to as "apparent heat flow" or "local heat flow".

WAIWERA SYSTEM(NEW ZEALAND)

The Waiwera hot springs are located about 35 km N of Auckland; the reservoir is probably created by the intersection of two fracture zones. The fracture zones appear to be 500 m wide (Alvarez, 1986). The reservoir consists of an upper (secondary) reservoir in about 400 m thick Tertiary rocks (sandstones and siltstones of the Waitemata Group) which is underlain by a less permeable Jurrassic greywacke basement where the intersection of the fracture zones has created a deeper (primary) reservoir which can be approximated by a vertical cylindrical column. The geological and hydrological setting of the prospect has been described in detail(ARWB, 1980,1986).

In the natural state, the system discharges a few kg/s of thermal water at about 45°C. The secondary reservoir has been exploited during the last 15 years by pumping of up to 25 kg/s from 100 to 400 m deep wells (maximum fluid temperature was 52°C) causing a small drop in temperature (up to -0.4°C/yr). The hot springs ceased to flow in 1978-a result of the pressure drop in the upper reservoir. The regional terrestrial heat flow is about 85mW/m^2; the local heat flow about 4 km away from the hot springs in the Orea well is only about 65 mW/m^2 (Pandy,1981).

The Waiwera system was simulated by computer modelling (modified SHAFT 79 program; Pruess and Schroeder, 1980; O'Sullivan, 1985) by assuming cylindrical symmetry. The permeability structure of the reservoir and the recharge blocks was obtained by a trial and error method, modifying permeability and geometry of individual blocks until good fits were obtained for the following matching parameters: stable temperature in up to 425 m wells in upper (Tertiary) reservoir; pressure changes in the upper reservoir as a function of the known, past production; heat flow in one control well outside the reservoir; and time variable changes in chloride concentration in the upper reservoir.

The best fit model has the following permeability structure:

1. Upper(Tertiary) reservoir: depth d=0-0.4 km; radius r=0.25 km, permeability $k=1x10^{-13}m^2$ (extended in a smaller N section to a distance of 4 km).
2. Lower (fracture zone) basement reservoir: d=0.4-4 km; r=0.25 km, $k=3x10^{-13}m^2$.
3. Basement outside fracture zone: d=0.4-4 km; r=4 km, $k=5x10^{-16}m^2$.
4. Deeper basement layer with minor permeability: d=4-6 km; r=4 km; $k=1x10^{-16}m^2$.

Computed temperatures, changes in temperature and (drawdown) pressure caused by production, and apparent heat flow values outside the system are all consistent with observed data. The pattern of the apparent heat flow between 0 to 100 m depth along a surface profile, as predicted by the best fit model, is shown in Fig.1. It can be seen that deep horizontal radial inflow of fluids reduce the terrestrial heat flow outside, up to a distance of 4 km, to about 60 mW/m^2 (over an area of about 50 km^2). The model predicts a natural upflow rate of about 4.5 kg/s and a natural heat loss of about 1.3 MW, with an apparent surface heat flow of about 840 mW/m^2 in the centre of the discharge area (See Fig.1).

FUZHOU SYSTEM (P R CHINA)

The system occurs beneath the town of Fuzhou in the Fuxien Province(S E China); its primary reservoir consists of a steeply dipping fracture zone, about 100 m wide, dissecting thick Cretaceous granite along which thermal waters rise over a length of about 6 km. The primary reservoir is covered by a thin(50 m) layer of Quaternary sediments containing confined aquifers where thermal fluids move laterally away from the feeding fracture zone. Neglecting edge effects, the reservoir can be modelled in terms of a two-dimensional structure. Details of the Fuzhou system have been published(Huang and Goff,1986).

In its natural state the system transferred at least 3.5 MW, as indicated by conductive losses at the surface, and discharged 3 kg/s of thermal water at 50 to 60°C by thermal springs. The fracture zone reservoir has been exploited during the last 15 years by pumping of up to 150 kg/s (in 1982) from 500 to 900 m deep wells (wellhead temperature up to 90°C); up to 50 kg/s were abstracted from the shallow Quaternary aquifers. As a result of past abstraction, the pressure in the primary reservoir decreased by at least 3 bars although the temperature decreased only slightly (about -0.5°C/yr). The temperature changes in the shallow aquifer were much greater (probably up to 10°C), although production history and reservoir response is poorly documented. The natural springs ceased shortly after production from the shallow aquifer began. The average terrestrial heat flow of the Fuzhou region, where large granite complexes are exposed, has been estimated to be at least 80 mW/m^2 (Wang Tianfeng et al., 1986). Heat flow data outside the reservoir from more distant wells were not available.

The Fuzhou system was modelled using the same approach as that developed for the simulation of the Waiwera system. Matching parameters in this case were: undisturbed temperature profiles of deep wells (up to 900 m) standing both inside and outside the fracture zone; undisturbed temperature profiles of shallow wells in the shallow Quaternary aquifers; spatial changes in chloride concentration; initial wellhead pressures and approximate values for the pressure drawdown in the primary reservoir.

The best fit model showed the following permeability structures:

1. Two Quaternary aquifers: d=15 m each, $k=1x10^{-14}m^2$ and $1x10^{-13}m^2$ respectively sandwiched between low permeability sedimentary layers with $k=5x10^{-16}m^2$.
2. Permeable fracture zone: depth d extended from 0.05 to 7 km; permeability k decreasing in 1 km interval from $5x10^{-13}$ m^2 by almost one order of magnitude at 6 km depth.
3. Granite basement outside fracture zone: d=0.05 to 7 km; $k=5x10^{-16}m^2$.

The model reproduces the natural state temperatures inside and outside the fracture zone, the spatial variation in chloride content, and gave values for pressure and temperature changes in the primary reservoir which are of the same order of magnitude as observed values. The deep crustal heat flow was retained as parameters (best fit value is 90 mW/m^2); the decrease in heat-generating capacity of the granite basement was neglected. Apparent heat flows were computed for various levels along a profile which runs perpendicular to the fracture zone(see Fig.2). This figure shows that the apparent heat flow is reduced to values of about 30 to 40 mW/m^2 at distances of more than 7 km away from the fracture (depth range 0.05 to 2.7 km); even at depths between 2.7 to 5.2 km, the value is still low (about 60 mW/m^2). Although the well data provide poor constraints for the deeper permeability structure, the model demonstrates that a significant amount of crustal heat can be transferred from the recharge area into the reservoir. The model predicts that , in its natural state, about 15 kg/s of thermal water moves through the fracture zone, transferring about 5 MW.

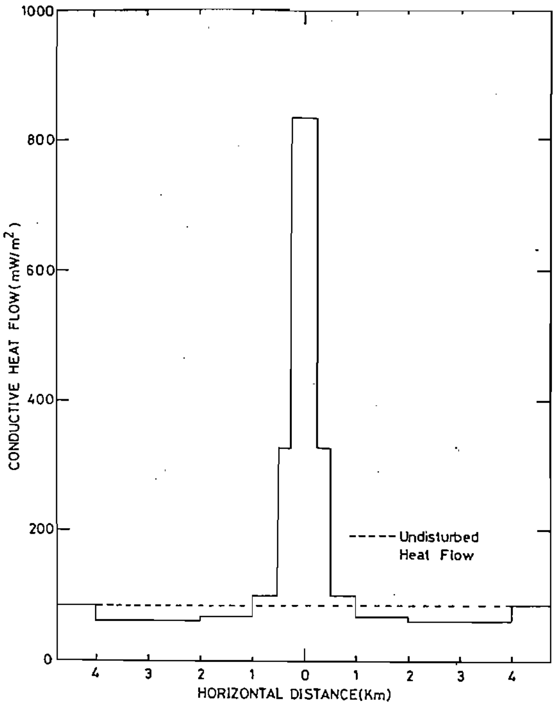

Fig.1 Profiles of calculated conductive heat flow(0 to 100 m depth) around Waiwera hot springs.

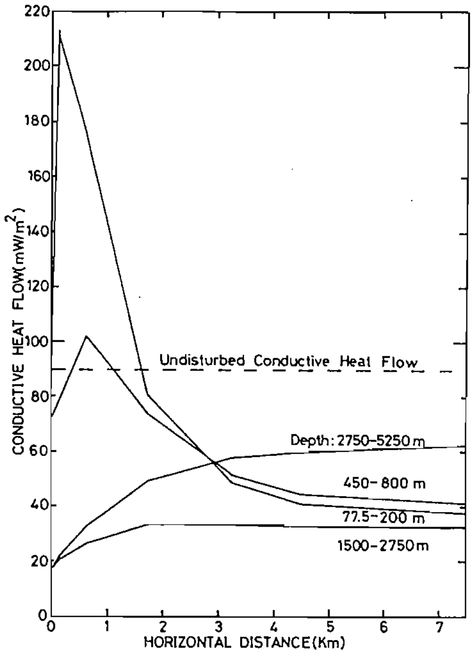

Fig.2 Profiles of calculated conductive heat flow at different depths outside the Fuzhou geothermal reservoir. (The fracture zone lies at the origin of the horizontal axis.)

DISCUSSION

Simulation of the complete secular convection of two low temperature fracture zone systems has shown that, even for basement rocks of low permeability (order of 10^{-16} m^2), deep penetration of meteoric waters is required to transfer heat from the upper 5 km of the crust towards the fracture zones. Initially this causes a significant cooling of upper crustal rocks in the recharge area; when steady state convection is reached, some heat supplied by the undisturved terrestrial heat flow is transferred in to the reservoir. In the case of the Waiwera system, the crustal heat flow is reduced by about 20 mW/m^2 within a radius of about 4 km; at Fuzhou the heat flow is probably reduced by about 50 mW/m^2 for distances greater than 7 km away from the fracture reservoir. The setting up time for each circulation pattern until steady state convection occurs is large, and was found to be about $2x10^6$ yr for both systems. Low temperature systems of the Waiwera/Fuzhou type are therefore rather old systems.

The cooling effect in the recharge areas is shown for both systems in Figs. 3 and 4, where predicted crustal temperature profiles are shown; the temperature data were taken from the best fit models. It is of interest to note that the temperature at the bottom of the fracture zone is significantly lower than that given by the undisturbed terrestrial heat flow (see Fig.4). Crustal temperatures below the deepest level of circulation should also be lower beneath the whole recharge area than those outside (see Fig.3).

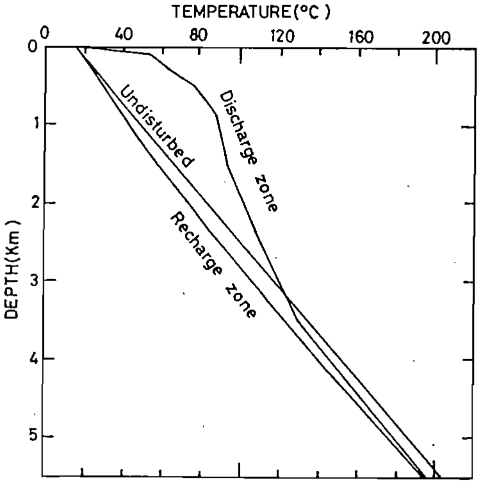

Fig.3 Calculated disturbed and undisturbed crustal temperature profiles of the Waiwera geothermal prospect.

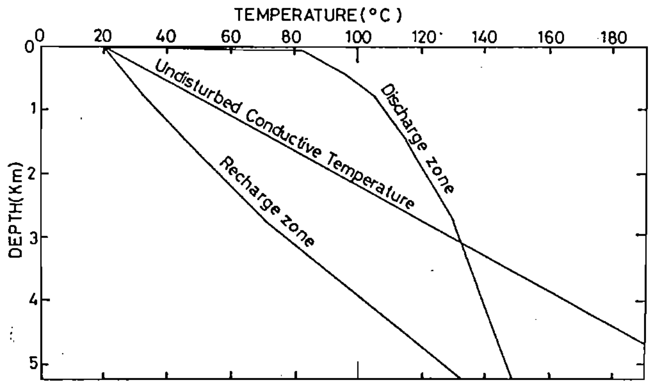

Fig.4 Calculated disturbed and undisturbed crustal temperature profiles of the Fuzhou geothermal prospect.

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