PROCEEDINGS, Fourteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 24-26, 1989
SGP-TR-122

# THE FUZHOU GEOTHERMAL SYSTEM (P.R. CHINA): NATURAL STATE AND EXPLOITATION MODELLING STUDY OF A LOW TEMPERATURE, FRACTURE ZONE SYSTEM

M.P. Hochstein[1), S. Ehara[2), Yang Zhongke[1)

1) Geothermal Institute, University of Auckland, New Zealand
2) Dept of Mining, School of Engineering, Kyushu University, Fukuoka, Japan

## ABSTRACT

A conceptual model is presented which explains the likely heat and mass transfer of the Fuzhou system in the natural and exploited state. The model was extended to 7 km depth to simulate a deep heat sweep of naturally convecting meteoric waters in a granitic crust. Convection is controlled by the high permeability (order of E-13m$^2$) of the fracture zone, the heatflow at the sweep base, as well as width and axial extent of the fracture zone. Recharge is controlled by a shallow, confined, highly permeable, Quaternary aquifer.

## INTRODUCTION

The Fuzhou system (Fujian Province, China) has been described by *Huang and Goff (1986);* the study is based on an earlier report by *Huang (1983)*. The Fuzhou prospect is a low temperature, fracture zone system where heat is transferred by convection, involving deeply penetrating meteoric waters, from a resource base in the granitic upper crust to the surface. Thermal fluids ascend in a narrow, 100m wide, steeply dipping fracture zone in granites over a length of about 5-6 km ($T \leq 100°C$ at 500m depth in the fracture); the fluids are discharged into a thin (15m), extensive Quaternary (Q) aquifer at 50m depth. A vertical permeability barrier divides the system into a N- and a S-half sector. The terrain is rather flat (mean elevation 4m asl) except for higher terrain 5 to 10 km away in the N and E. A map of the prospect is shown in Fig. 1.

Little is known about fracture zone systems although they are common in SE Asia, often associated with extensive granites. The summary term "geothermal fracture zone system" has been used by *Hochstein (1988)* to classify these systems. They have some affinity with the theoretical models of *Sorey (1975)* and *Kassoy and Zebib (1978)* which demonstrate that fluid convection can occur in a narrow fracture zone which stands in a normal temperature, crustal setting.

The Fuzhou system has been exploited since about 1970 by shallow wells (Q-aquifer) and deep wells (within the fracture zone); abstraction increased continuously, reaching about 200 kg/s by 1982. Recently we obtained selected data from a report by the *Fujian Hydrogeological Team (1985)* which contains information describing the average pressure response in the Q-aquifer and average changes in temperature of produced fluids. Since the Fuzhou prospect is one of the few fracture zone systems exploited on a large scale, we used the available data to simulate likely heat and mass transfer for such a fracture zone system. Another aim of this study was to investigate the conditions under which such a system can develop.

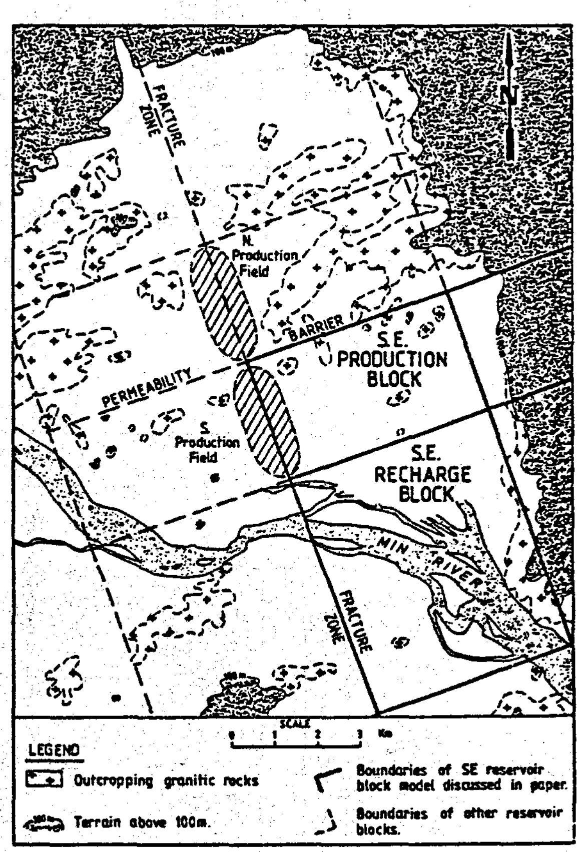
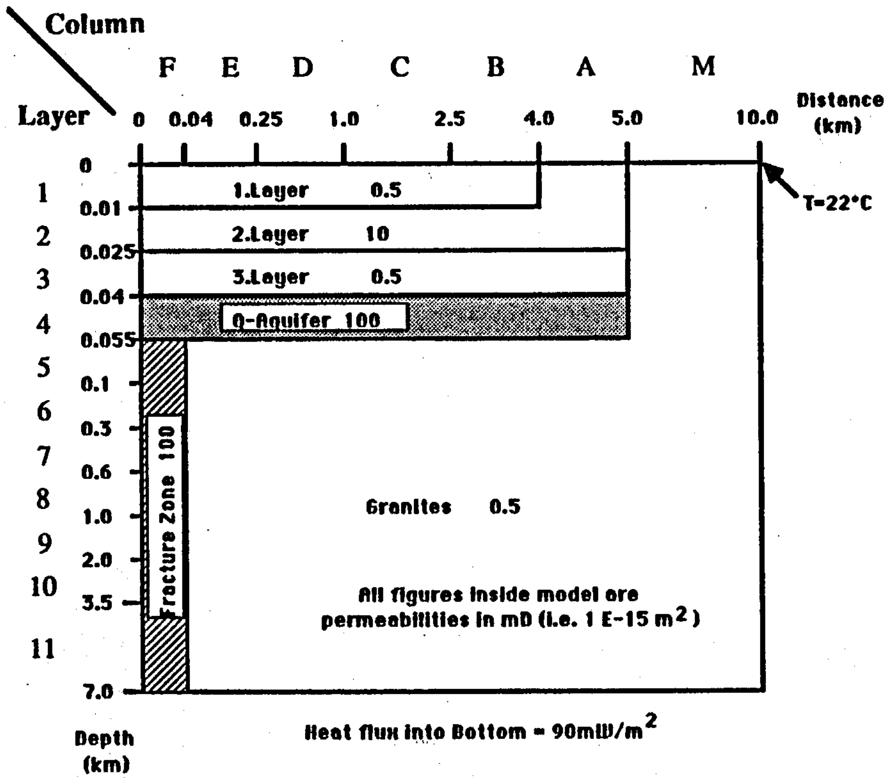
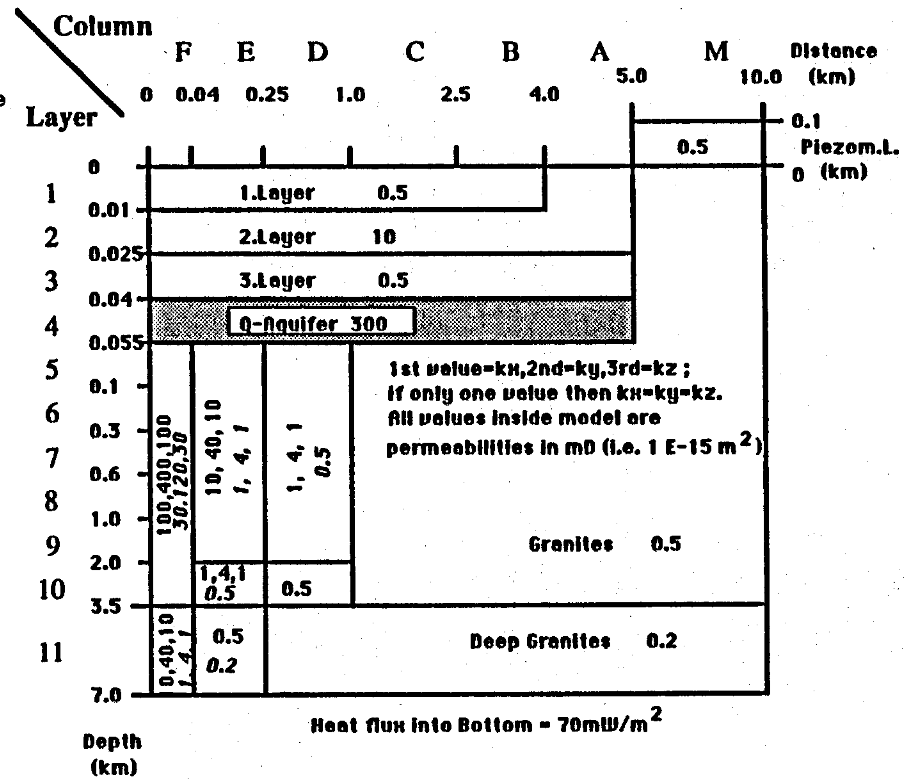



Fig. 1: Map of Fuzhou geothermal prospect. The location of the fracture zone and the ENE-trending, central, low permeability barrier are shown which were used to define quarter blocks of the model discussed in the text. Also shown is part of the SE quarter block and the SE adjacent recharge blocks (see Fig. 6).




| Layer | Sat.Density ($10^3 kg/m^3$) | Porosity | Therm.Conductivity (W/°C m) |
|---|---|---|---|
| Surface | 2.2 | 0.03 | 1 |
| 2nd Layer | 2.2 | 0.2 | 1 |
| 3rd Layer | 2.2 | 0.03 | 1 |
| Q-Aquifer | 2.2 | 0.2 | 1 |
| Fracture Zone | 2.6 | 0.1 | 2.5 |
| Granites | 2.6 | 0.01 | 2.5 |

TABLE 1: Diagram summarizing all parameters used for simulation of the natural state model described in the text.




| Layer | Sat.Density ($10^3 kg/m^3$) | Porosity | Therm.Conductivity (W/°C m) |
|---|---|---|---|
| Surface | 2.2 | 0.15 | 1.2 |
| 2nd Layer | 2.2 | 0.2 | 1.3 |
| 3rd Layer | 2.2 | 0.15 | 1.2 |
| Q-Aquifer | 2.2 | 0.2 | 1.3 |
| F.Zone(F11=E9) | 2.6 | 0.1 *(0.02, F11)* | 2.5 |
| E5-E9 (E10=D9) | 2.6 | 0.05 *(0.02,E5-9)* | 2.5 |
| D5-D9 (D10=C10) | 2.6 | 0.02 *(0.01,D5-11)* | 2.5 |
| Granites | 2.6 | 0.01 | 2.5 |

TABLE 2: Diagram summarizing parameters used for simulation of the production state model described in the text. Values and comments in italics refer to the end-on recharge blocks (covering the extended fracture zone); all other values are common to recharge and production quarter block model.

## NATURAL STATE MODEL (RESTRAINTS)

If one plots the temperature in the Q-aquifer versus distance from the fault trace, one finds that temperatures decrease almost exponentially (Fig. 2). The plot shows no systematic difference between data from the N and the S sector. Chloride data cited in *Huang and Goff (1986)* indicate an almost constant concentration of this constituent in the fracture zone and the Q-aquifer in each sector. This, in turn, implies that the shallow aquifer is overlain by rather impermeable sediments. As will be shown later, the T-data plotted in Fig. 2 (based on measurements in 1977) have already been affected by the production of fluids prior to 1977. Since only a small amount (a few kg/s) of hot water was discharged by springs before 1970, it can be inferred that most of the heat was lost by conduction through the shallow overburden and through the walls of the fracture zone. Using data shown in Figs. 2 and 3, these losses were estimated to be at least 5 MW, pointing to an upflow rate of $\geq 15$ kg/s of fluids at 100 °C (at 500m depth). The mean annual temperature is about 22°C.

A plot of the temperatures in deep wells at 450m depth versus distance from the fracture zone is shown in Fig. 3; again, an exponential decrease is indicated. The effect of the dip (about 75° to the E) of the fracture zone has been eliminated by using reduced horizontal distances. For simulation, the effect of the dip was also neglected and a vertical fracture zone of equivalent width was used instead. The model was therefore reduced to one with axial symmetry, i.e. with respect to the axial plane of the fracture zone (half width model). The presence of the vertical permeability barrier perpendicular to the fracture zone (see Fig. 1), which prevents mixing of fluids across the barrier, as indicated by different mean chloride values in each sector *(Huang, 1983)*, allowed us to reduce the model further to a quarter block model.

Although the dimension of the outer part of any natural state model is not critical because of equivalence, we tried to use a realistic length for the block model. Heatflow measure-ments in granites about 10 km S of the prospect had shown anomalously low flux values (of the order of <50 $mW/m^2$; *Huang Shaopeng, pers. comm.)* whereas the average heatflow of the greater Fuzhou region appears to be about 80 $mW/m^2$ *(Wang Tianfeng et al., 1986)*. A length of 10 km and a width of 3 km was therefore adopted for the quarter block model. The thermodynamic Na/K geo-thermometer *(Giggenbach, 1986)* indicates deep equilibrium temperatures of about 150°C which prevail at the resource base. Using the observed reduced heat flow directly outside the system, the Na/K equilibrium temperature points to depths of the order of 7 km for the deepest sweep. Thus the dimensions of the quarter block model were defined.

There were some limited data which restrained the permeability structure of the natural state model. Specific yield tests of wells producing from the Q-aquifer (N sector) pointed to permeabilities of the order of 100 to 300 millidarcy (mD); the very small specific capacities of wells in granites away from the fracture zone indicated permeabilities of the order of a few mD. Although fracture permeability will be dominant in the fracture zone, data were insufficient to assess this parameter. Instead, we used an anisotropic structure limiting the vertical permeability to 100 mD since this value had been used in the theoretical study of a fracture zone by *Kassoy and Zebib (1978)*. In their model they had used a 100m wide fracture which transferred about 4.5 kg/s of fluids per km with T = 67°C at the surface in the steady state model, values similar to those observed at Fuzhou.

For simulation, a modified SHAFT 79 program *(O'Sullivan et al., 1983; Preuss and Schroeder, 1979)* was used; recharge was controlled by the vertical permeability of the top layers and by maintaining constant T and p at the free surface. To allow for granites outcropping in some inner blocks (see Fig. 1), the same low permeability (0.5 mD) was assigned to the surface layer and outcropping granites and metamorphics, which implies homogenous infiltration for the whole area.

## NATURAL STATE MODEL (RESULTS)

The approximate structure of the steady state model is shown in Fig. 4. A trial and error method was used to refine the gross permeability structure of the initial model. For the simulation it was assumed that the fracture zone had been created at time t = 0, and that the temperature and pressure field was that given by an inferred undisturbed terrestrial heat flow (initially 80 $mW/m^2$), neglecting the heat-generating capacity of the granites between resource base and surface. The models were run until steady state conditions were reached; observed temperatures in wells and natural heat loss were used as matching parameters.

Parameters of one of the best fit models which reproduces approximately the observed data are listed in Table 1; the steady state temperatures of this model are shown in Figs. 2 and 3. For this model, steady state conditions were reached after about $t = 2 \times 10^6$ yrs. The significant cooling effects at the resource base (layer 11 in Table 1) have been described recently elsewhere *(Ehara et al., 1988)*.

Although the model listed in Table 1 reproduces the gross temperature structure of the Fuzhou Field, it is a very simple model which has various unrealistic features, namely:

1. too high heatflow at the bottom (90 $mW/m^2$); such high value was necessary to match the observed high temperatures in the fracture zone;
2. horizontal permeabilities are not restrained; the model does not allow for "cross-flow";
3. likely changes in permeability with depth were neglected;
4. significant permeability is not only confined to the fracture zone, but extends also outside as indicated by structural data *(Huang, 1983)* and minor productivity of deep wells standing close to the fracture zone.

Despite these limitations, simulation of steady state conditions has shown that:

natural convection in a thick crustal section of granites with an overall low permeability can be set up by the creation of a deep-reaching fracture zone; for this convection to occur, the dimensions of the block model must be finite.

## REVISED MODEL ALLOWING FOR EFFECTS OF PRODUCTION

Production of hot water from the Q-aquifer in the N sector started in the mid 1960s using shallow wells (av. yield 0.5 to 2 kg/s); deep wells were drilled to intersect the fracture zone from 1970 onwards (10 of these wells have yields between 5-15 kg/s). No detailed production history is known, and flow meters were only installed in 1984; no systematic monitoring of well pressures has been undertaken except for sporadic measurement of water levels in presumably low productivity wells. From interviews and sparse data in the 1985 report of the Fujian Team we constructed idealized abstraction scenarios for equivalent quarter blocks in the N and S sector which are shown in Fig. 5; plotted also are average pressure drops in the Q-aquifer for the period 1977-1983. Only abstraction rates after 1984 are well documented.

It is obvious that, with the sparse data shown in Fig. 5, the pressure response of any realistic model cannot be fully tested, but the data provide some restraints which allowed revision of the natural state model. For this, it was assumed that the observed average pressure drop in the Q-aquifer is the mean of most of the wells shown in Fig. 2 which lie between 150 to 600m away from the fracture zone. Simulation of the pressure response was limited initially to the S sector where production comes almost entirely from the fracture zone.

Using the inferred abstraction scenario for the S sector it was found that the natural state model responded with too large pressure drops, amounting, for example, to -1.5 to -5 bars in the Q-aquifer after only 8 years production (i.e. 1970 to 1978) whereas the reported average drop in pressure was no more than about 2 bars after 13 yrs production in the S sector (about half as high as that in the N sector). Obviously, the natural state model did not allow for sufficient recharge.

A sensitivity analysis of various model parameters showed that each of the following reduced somewhat the pressure drop (in comparison with that of the natural state model):

(a) increase in permeability of Q-aquifer to about 300 mD and moderate increase in thickness of Q-aquifer;

(b) increase in permeability of granites in the blocks adjacent to the fracture zone by up to one order of magnitude;

(c) addition of two end-on recharge blocks (dimension 3 x 10 x 7 km each) allowing for some crossflow and for higher piezo-metric levels in the outermost blocks to simulate gross terrain effects.

Inclusion of (c) produced the interesting result that, by increasing the vertical permeability in the fracture zone of the outer block above a critical value, the fluid flow in the fracture zone in the "production" block (see Fig. 6) could be reversed (critical value in our case was 30 mD). The high permeability of fracture zones associated with natural convection must therefore be confined in axial direction.

None of the three changes listed above was sufficient to produce a pressure response similar to that shown in Fig. 5. All three modifications were then incorporated in the revised model shown in Fig. 6, with the additional modifications:

(d) reduction of heatflow at the bottom from 90 to 70 mW/m$^2$ to reduce the rather high temperatures in the fracture zone caused by (c);

(e) reduction of permeability with depth for the granites by up to half an order of magnitude; for the same reason as described in (d).

(f) slight increase in thermal conductivity of the sedimentary cover; to reduce too high temperatures in the Q-aquifer caused by (c).

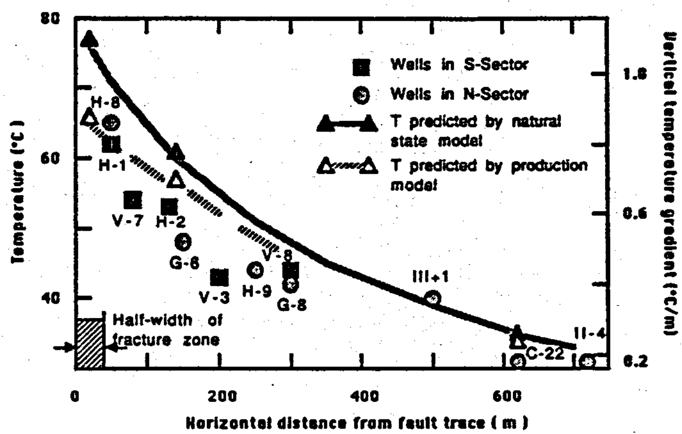



Fig. 2: Temperature in Q-aquifer (50m depth) plotted versus distance from median fault trace. Distances and temperatures were taken from *Huang (1983)*. All temperatures were measured in 1977. Also shown are theoretical temperatures of the natural state model (Table 1) and temperatures of the production model (Table 2) after 10 years production (1980) in the S sector.

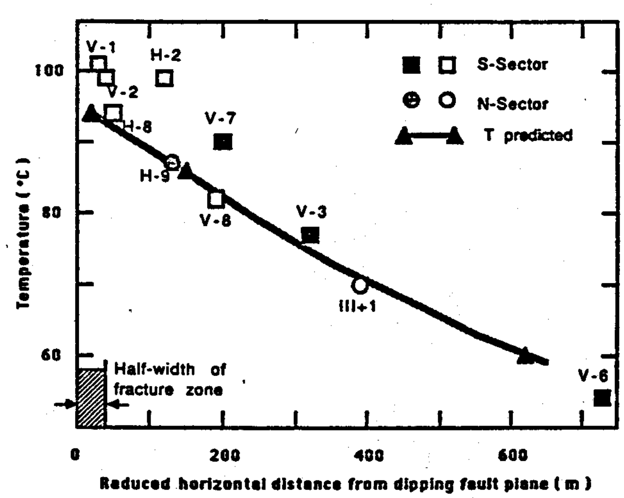



Fig. 3: Temperature at 450m depth plotted versus reduced horizontal distance (i.e. horizontal distance between well and median fault plane for a 75° E-dipping plane at 450m depth). Shown also are the temperatures predicted by the natural state and the production model which are almost the same.

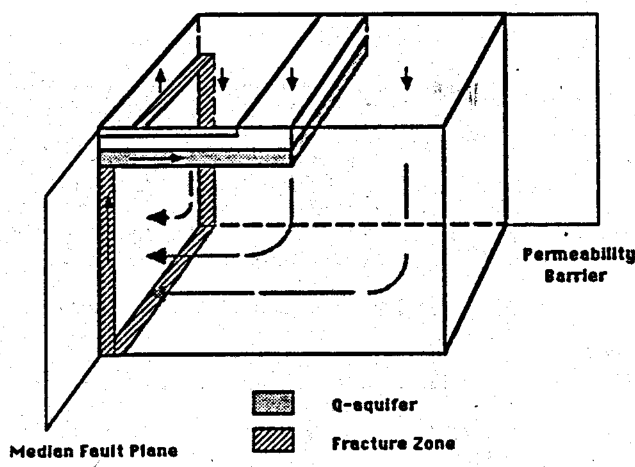



Fig. 4: Schematic diagram of natural state, quarter block model (for details, see Table 1).

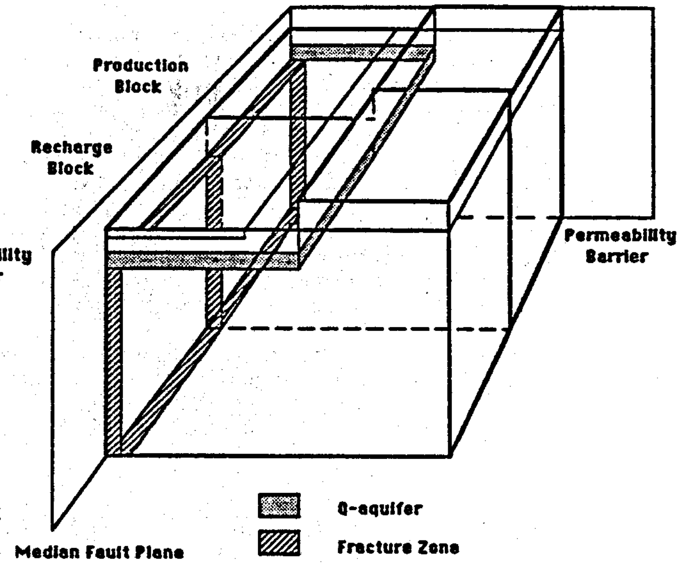



Fig. 6: Schematic diagram of production stage, quarter block model (for details, see Table 2).

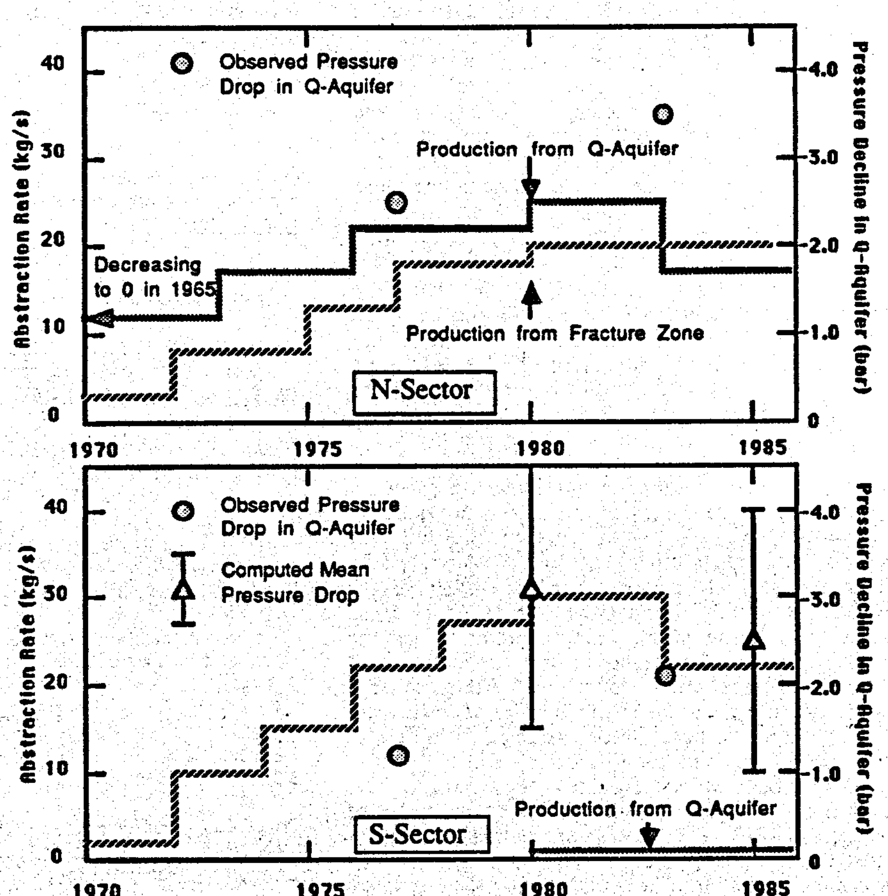



Fig. 5: Inferred production scenario (1970-1985) for quarter block models in the N and S sector of the Fuzhou field; only abstraction rates from 1984 onwards are based on measured flow rates. Also shown are observed average pressure drop in Q-aquifer between 1977 and 1983 (presumably from wells which lie between 100 and 600m away from the fracture zone) and computed mean pressure drop for 1980 and 1985 (error bars give Δp in D4 and E4 blocks).

With these modifications we obtained a production model shown in Fig. 6 (parameters listed in Table 2) which, for distances between 200 and 600m away from the fracture zone, produces pressure drops (-2.5 to -3 bars) in the Q-aquifer which are of the same order of magnitude as the observed mean value (about -2 bar). In addition, temperatures in the Q-aquifer were obtained for 1977 which are somewhat closer to the observed data than those given by the steady state model (see Fig. 2). Using the abstraction scenario of the N sector, the model also reproduces higher pressure drops as observed in Q-aquifer wells in the N sector but the computed values are significantly higher (up to 50%). Since the locality of wells for which piezometric level changes were observed are not known, further refinement of the "production" model is not justified. An interesting finding is that the temperature at the bottom of the fracture zone (block F11 in Fig. 6) is about 154°C, close to that indicated by the Na/K geothermometer.

## SUMMARY

Simulation of the Fuzhou geothermal system has shown that in the presence of a deep-reaching, highly permeable fracture zone, natural convection can be established, even within rocks with low overall permeability, such as granites. For a steady state system to develop, the size of the convection cell must be finite, and the axial extent of the highly permeable fracture zone must be limited (about 3 km in the case of the Fuzhou system). High temperatures in the fracture zone can be the result of the combination of any of the following parameters: high permeability and extended width of the fracture zone, higher heatflow at the resource base, significant horizontal pressure gradient between recharge blocks and fracture zone (i.e. higher piezometric levels in the outer recharge blocks). By combining all three, we could simulate boiling point temperatures in the Q-aquifer using the "production" model shown in Table 2. This might explain why some wide fracture zone systems, like that of San Kamphaeng in Thailand *(Hochstein et al., 1987)*, can discharge hot water at boiling point at the surface in the natural state.

The study has also shown that, with respect to recharge characteristics under exploitation, the Fuzhou prospect is rather anomalous since dominant recharge is provided by a highly permeable, shallow aquifer. Analysis of the fluid flow of the "production" model indicates that about 98% of all produced fluids are recharged after 10 years of production (about 55% from Q-aquifer and 43% from upflow in the fracture zone), which explains in part the rather small pressure drop resulting from the exploitation of such a small reservoir. Since most of this recharge enters the fracture zone at the top (i.e. by downflow), a significant amount of heat can be extracted from the hot rocks inside the fracture zone. In this case, the energy potential can be obtained from a simple stored heat calculation or by using the planar fracture assessment of *Bodvarsson (1974)*. This assessment cannot be used for fracture zone systems which are not associated with a recharging shallow aquifer and which would exhibit significantly lower energy and mass flow potentials than the Fuzhou system.

## ACKNOWLEDGEMENT

We would like to acknowledge the assistance of Mr Zhang Zhenguo (Ministry of Geology, Beijing) who provided selected data of the report compiled by the Fujian Hydrogeological Team. A/Prof. M.J. O'Sullivan assisted with simulation of the initial models. A/Prof. S. Ehara received the Mitsubishi New Zealand Ltd. 1987 Fellowship to undertake part of this study at the Geothermal Institute, University of Auckland.

At the proof stage we found that a map used originally for defining the width of the quarter block models contained a small scale error; the actual width is about 2.5 km instead of 3 km used here. The scale of Fig. 1, however, is correct. By proportional increase of permeability of all blocks, the same heat and mass transfer pattern can be obtained as presented in this paper.

## REFERENCES

Bodvarsson, G. (1974). "Geothermal Resource energetics." Geothermics 3, 83-92.

Ehara, S., Hochstein, M.P., O'Sullivan, M.J. (1988). "Redistribution of terrestrial heat flow by deep circulating meteoric waters recharging low T geothermal systems." Proc. of Int. Symposium on Geothermal Energy, 1988, Kumamotu and Beppu (Japan), 618-621.

Fujian Hydrogeological Team (1985). "Studies of Fuzhou geothermal prospect." (Unpublished report), Fuzhou (in Chinese).

Giggenbach, W.F. (1986). "Graphical techniques for the evaluation of water/rock equilibration conditions by use of Na, K, Mg and Ca contents of discharged waters." Proc. 8th NZ Geothermal Workshop 1986 (Auckland), 37-43.

Hochstein, M.P. (1988). "Assessment and modelling of geothermal reservoirs (small utilization schemes)." Geothermics 17, 15-49.

Hochstein, M.P., O'Sullivan, M.J., Bhaddee, S. (1987). "Modelling of San Kamphaeng geothermal reservoir. Proc. 9th NZ Geothermal Workshop 1987 (Auckland), 159-162.

Huang, H.F. (1983). "Characteristics and reservoir model of the Fuzhou geothermal field, China". Geoth. Institute Report 83.08, University of Auckland (NZ), 52 pp.

Huang, H.F., Goff, F. (1986). "Hydro-geochemistry and reservoir model of Fuzhou geothermal field, China". Journal Volcanology and Geothermal Research 27, 203-227.

Kassoy, D.R., Sebib, A. (1978). "Convection fluid dynamics in a model of a fault zone in the Earth's crust." J. Fluid Mechanics 88, 769-792.

O'Sullivan, M.J., Zyvoloski, G., Blakeley, M.R. (1983). "Computer modelling of geothermal reservoirs." School of Engineering report 318, Univ. of Auckland (NZ).

Preuss, K., Schroeder, R.C. (1979). "Geothermal reservoir simulation with SHAFT 79." Proc. 5th Workshop on Geothermal Reservoir Engineering (Stanford), 183-188.

Sorey, M.L. (1975). "Numerical modelling of liquid geothermal systems." U.S. Geological Survey, Menlo Park (Calif.), Open File Report 75-613.

Wan Tianfeng, Tong, Y., Lin, S., Zheng, W. (1986). "Silica geothermometry estimates of heatflow in the Fujian Province (P.R. China)". Proc. 8th NZ Workshop 1986 (Auckland), 195-197.