PROCEEDINGS, Fifteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 23-25, 1990
SGP-TR-130

Conceptual Model of the Zhangzhou low temperature system and its surrounding catchment (Fujian Province, P.R. China)

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Abstract

A regional hydrological model of the Zhangzhou Basin and its surrounding large catchment is presented. The model includes the Zhangzhou geothermal prospect in the centre, where fluids with a maximum temperatureof 120°C have been observed at 0.1 km depth. The model reproduces the observed low temperature gradients in nearby and distant deep wells, and explains the natural heat transfer (≥ 8.5 MW) of the prospect and the observed high temperatures of the inner reservoir. The Zhangzhou system is driven by terrain-induced forced convection causing deep heat sweeps in the upper crust down to at least 5 km depth. The natural fluid flow disturbs the crustal temperature field beneath the whole catchment (≥ 10,000 km^2).

Introduction

The Zhangzhou geothermal prospect lies in Fujian Province (P.R.China) in the SW part of an artesian basin, the Zhangzhou Basin, in the centre of a large catchment (about 10,000 km^2) drained by the Jiulong River (Fig. 1). The prospect is one of at least five low temperature systems which occur in fractured granitic host rocks along a broad, 50 km wide coastal strip of Fujian Province. At Zhangzhou, hot water with an average temperature of ~70°C is discharged at a rate of about 23 kg/s (Hu, 1989). The thermal anomaly, as defined by anomalous temperatures in shallow wells (50 m depth), covers an area of 4 km^2; allowing for conductive losses, it was found that the system transfers heat at a rate of ≥ 8.5 MW in the natural state. A short summary of the prospect has been given recently by Wang *et al.* (1989).

The Zhangzhou system has similarities with the Fuzhou low temperature system which also lies in the coastal strip of Fujian Province and which has already been modelled (Hochstein *et al.* 1989, 1990). Using all available data (Wang *et al.*, 1989; Dai *et al.*, 1988; Xu, 1988; Xiang *et al.*, 1988a, 1988b), a simple conceptual model of the Zhangzhou prospect has been developed recently by Hu (1989). In this paper, Hu's model has been modified to study various characteristics of a low temperature system in a well-defined artesian basin surrounded by a large catchment area with steep terrain. The study was extended by using a sensitivity analysis to assess limits for the overall permeability structure of the upper crust beneath the Zhangzhou catchment.

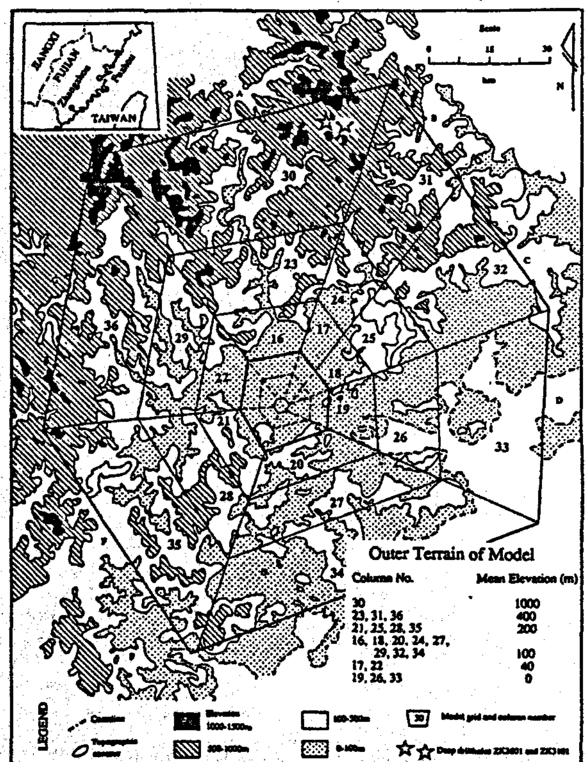

Fig. 1: Topography of Zhangzhou catchment. The Zhangzhou geothermal prospect lies in the innermost hexagon. A hexagonal grid is shown which divides the whole catchment into a set of vertical columns (total 36); the mean elevation of the numbered columns is listed in the legend. Smaller capital letters at the periphery of the largest hexagon define sectors mentioned in the text (i.e. column 30 lies in sector A).

Setting of the Zhangzhou geothermal prospect

The prospect lies almost in the centre of the large Zhangzhou catchment (Fig. 1); the boundaries, as given by the catchment divides, enclose an area of at least 10,000 km^2. Whereas the artesian Zhangzhou Basin (about 1000 km^2) has an average elevation of 50 m (a.s.l.), outer terrain in the N and W sectors of the catchment stands about 500 to 1000 m above sea level. The Zhangzhou thermal area lies close to the Jiulong River which drains the catchment (Fig. 3). The productive wells in the prospect stand 7-10 m above sea level, the river level at Zhangzhou being close to mean sea level.

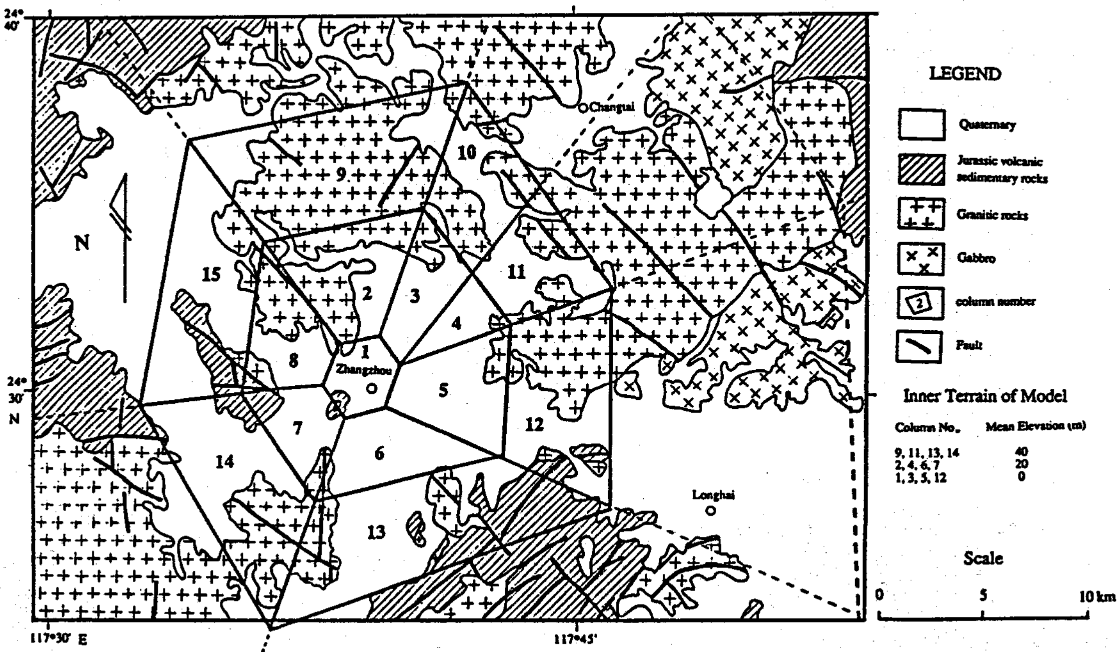

Fig. 2: Geology and tectonics (older faults) of the surface rocks in Zhangzhou Basin; also shown is the inner hexagonal grid of the model discussed in the paper and the mean elevation (see legend) of the numbered columns shown in the figure.

The basement rocks surrounding the Zhangzhou Basin consist mainly of Mesozoic granodiorites and metamorphic rocks of Jurassic age covered by thin (<50 m) Quaternary sediments inside the Basin; pockets of granodiorite are exposed throughout the basin (Fig. 2). The whole catchment is dissected by two sets of steeply dipping older faults striking NE and NW respectively (Fig. 2). Within the basin, sets of younger faults have been mapped trending NNE and WWN (Fig. 3). It has been postulated that the hot water in the Zhangzhou prospect ascends along highly permeable segments of the younger faults, especially at the intersection of these faults (Wang *et al.*, 1989; Hu, 1989).

More than 100 shallow holes (≤ 100 m depth) have been drilled in the Zhangzhou prospect over an area of 25 km^2. Isotemperature contours (Fig.3) based on temperatures at 50 m depth (Hu, 1989) indicate an inner reservoir (about 0.5 km^2) where the temperatures at this depth are greater than 60°C, and an outer reservoir (about 2.5 km^2) where 30°C > T > 60°C (Fig.3). The highest temperatures (120°C at 90 m depth) have been found in two shallow wells near the centre of the inner reservoir. Temperature profiles of a few selected wells along a NNE-trending profile across the Zhangzhou prospect are shown in Fig. 4. Since the temperature contours in Fig. 3 are elongated in the direction of 325°, it is possible that fluids might ascend along an older, unknown fracture zone with the same strike. All wells stand in granitic rocks.

There are only a few wells deeper than 200 m in the outer reservoir (see Fig. 4); another deep (800 m) well (ZR8) stands about 1.5 km NE from the centre of the inner reservoir (see Fig. 3) where bottom temperatures close to 80°C have been observed (Hu Shengbiao, pers. comm.); the well is non-productive but no other information is available. Most of the wells in the inner area are artesian wells and produce fluids at a rate typically about 6 kg/s.

The prospect has not yet been exploited, and the production response of the reservoir is unknown. Incomplete well tests indicate an order of magnitude difference in apparent natural flow velocities in the granodiorites between the inner and outer reservoir (Hu, 1989).

About 70 km to the north of the Zhangzhou prospect, at an elevation of about 1000 m, are two deep wells (600 and 800 m depth respectively) (Fig. 1) for which the apparent heat flow has been determined in detail (Hu, 1988). These wells stand in a sequence of granites and sandstones in the outer Zhangzhou catchment and indicate an anomalous low, apparent terrestrial heat flow of about 38 mW/m^2. The heat production capacity of the granites is rather high (average 4 to 4.5 10^{-6} W/m^3).

Since similar low apparent heat flow values have been observed in deep wells in higher terrain within other coastal catchments associated with low temperature systems in Fujian Province (Hu, pers. comm.), we had to allow for the possibility that terrain-induced, forced convection, which drives, for example, the Fuzhou geothermal system (Hochstein *et al.*, 1989, 1990), might disturb the terrestrial heat flow beneath the whole Zhangzhou catchment.

Origin of thermal fluids in Zhangzhou prospect

Stable isotope data (O^{18}, D) indicate that all thermal fluids are meteoric waters whose isotopic composition lies close to the meteoric water line (Wang *et al.*, 1989); the absence of any O^{18} shift indicates that temperatures of less than 200°C prevail at the deepest level of fluid-rock interaction. The thermal water in the inner reservoir is highly mineralized (up to 10 g/kg total solids), the water being a slightly alkaline NaCl-type water. Most of the mineralization is probably due to mixing of a less mineralized deep hot water with saline pore fluids which occur, for example, in cold wells lying to the E of the thermal prospect. Shallow wells elsewhere in the basin produce groundwater with less than 0.3 g/l total solids. The chalcedony geothermometer indicates equilibrium temperatures of about 122°C for fluids in the upper part of the inner reservoir (Hu, 1989). The plot of SiO_2 concentration versus bottom hole temperature intersects the chalcedony equilibrium curve at T = 140°C (Wang *et al.*, 1989).

Assuming that the saline (marine?) pore waters encountered in cold wells in the E part of the area descend to greater depth and that the Na and K concentrations are controlled by fluid interactions with feldspar in the deeper granites, Hu (1989) inferred that equilibrium temperatures of 170°C (using the Na-K geothermometer of Giggenbach, 1986) might prevail at the level of the deepest fluid path. Since the geochemistry of deep fluid samples has not been determined yet, it is not known whether the cation concentrations of the mixed, highly mineralized thermal waters are controlled by such fluid-rock interaction. The SiO_2 values in the mixed thermal water at Zhangzhou are slightly greater (120 mg/kg) than those of undiluted deep waters encountered in fractured granites at Fuzhou (90 mg/kg); therefore, it is possible that somewhat higher temperatures prevail at the sweepbase at Zhangzhou. At Fuzhou, the Na-K geothermometer (Giggenbach, 1986) indicates equilibrium temperatures of 155°C (Hochstein *et al.*, 1989).

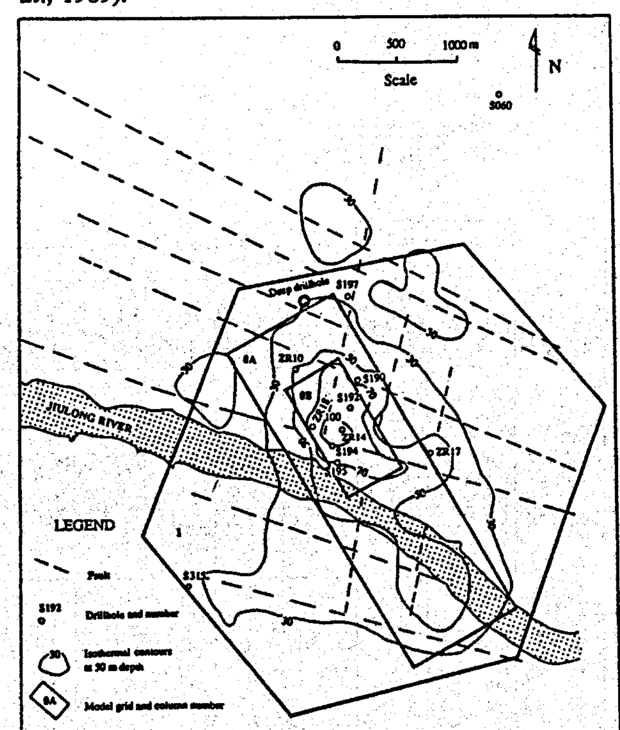

Fig. 3: Map showing the grid for the innermost hexagon (Zhangzhou geothermal prospect) which covers the area where anomalous temperatures have been observed in shallow wells. Using the isothermal contours based on temperatures at 50 m depth (Hu, 1989), the area has been divided into an inner reservoir (OB), an outer reservoir (OA), and a surrounding area (block 1), all lying within the hexagon. The map also shows the position of a set of younger faults (Hu, 1989) and the position of a few selected wells (see Fig. 4).

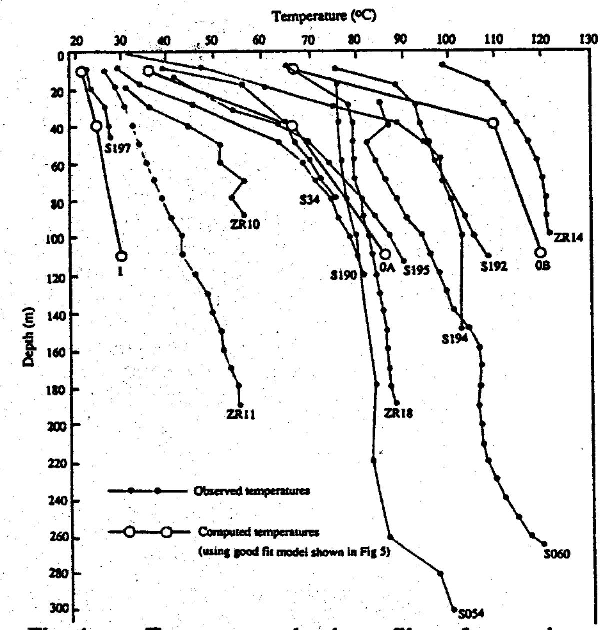

Fig. 4: Temperature-depth profiles of a number of selected wells in the Zhangzhou prospect (for position of the wells, see Fig. 3). Also shown by large circles are the computed downhole temperatures of the best fit model (Fig. 5) for fictitious wells lying in reservoir columns 1, OB, and OA.

Earlier conceptual models of the Zhangzhou system

Wang *et al.* (1989) already proposed a simple conceptual model where meteoric water in the catchment penetrates to depths of 3.5 to 4 km, sweeping heat along radially inward- directed paths with hot fluids ascending through a fractured reservoir of vertical, cylindrical shape. No data are given which define the permeability structure of this simple model. This model transfers heat at a rate of about 2 MW, which is half an order of magnitude lower than the natural heat loss cited by Hu (1989).

Hu (1989) constructed a reservoir model for an area of 2250 km^2 using a set of rectangular blocks which cover most of the Zhangzhou Basin but only a small part of the catchment area. The inner reservoir was approximated by a set of rectangular columns covering 0.32 km^2; the outer reservoir blocks covered 4 km^2. The model was extended to a depth of 8 km. The permeability structure was assumed to be similar to that of the Fuzhou system (Hochstein *et al.*, 1989). For simulation, a modified SHAFT program was used (O'Sullivan *et al.*, 1983). The observed shallow temperatures and natural heat loss could be matched by using a verical permeability of 100 millidarcy (mD) for the inner fracture zone blocks and an average permeability of 0.5 mD for the surrounding granitic basement rocks down to a depth of 4 km; the permeability was reduced by one order of magnitude for the deepest part of the fracture and the deepest layer, respectively.

Although this model allowed for recharge from higher-standing terrain in the NW, the recharge area covered only a small part of the Zhangzhou catchment. In this study we investigate whether a suitable model can be constructed which covers the whole Zhangzhou catchment and whether the observed temperature gradients in deep wells in the outer, higher terrain can be used as an additional matching parameter.

Revised model of the Zhangzhou system

The Zhangzhou catchment was covered by a hexagonal grid (Figs. 1 and 2), and mean heights were constructed from various radial profiles for each segment inside the grid. Some terrain profiles are shown in Figs. 6a, b, c. The grid was extended to the inferred catchment divides; a large block (not shown in Fig. 1) was used as a sink at the periphery of the outer hexagon covering the ocean area. It was assumed that the mean piezometric level of each segment in the grid is close to the mean height. All segments (columns) were divided into a set of layers (Fig.5). For terrain-induced forced convection, infiltration has to balance discharge; recharge was controlled by the permeability of the top layers and by maintaining constant temperature and pressure (allowing for the adiabatic lapse rate and a mean standard atmosphere) at the surfaces of the model. For simulation, a modified SHAFT 79 program was used.

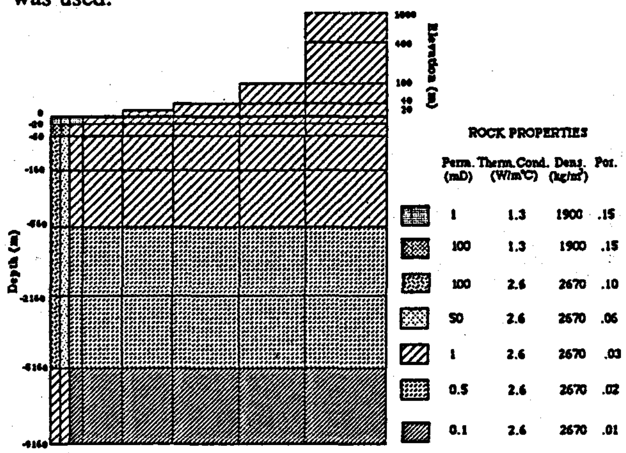

Fig. 5: Schematic cross-section along a radial profile from the centre of Zhangzhou prospect to the catchment boundary. The top of the columns represents the mean piezometric level (given by the mean elevation of each column). The physical properties of the rocks at various levels are listed in the legend. The change in permeability with depth is approximated by a three-layer structure.

The Zhangzhou thermal reservoir was placed inside the innermost hexagon (Fig. 3); the highly permeable, thin Quaternary layer, from which most of the production of the shallow wells is derived, was only extended to cover the innermost hexagon. Since modelling of the Fuzhou system has shown that thermal systems inside artesian basins are driven by terrain-induced forced convection, we did not attempt to model the effects of free convection for the flat part of the Zhangzhou Basin but modelled the likely convection pattern beneath the whole Zhangzhou catchment. It was assumed that fracture permeability is caused by some regular sets of fractures and that for any large block this fracture permeability can be replaced by an equivalent homogeneous permeability. As matching parameters, we used:

1. the observed temperatures in the inner and outer Zhangzhou reservoir,
2. the inferred total natural heat loss of the Zhangzhou prospect (≥8.5 MW), and
3. observed temperature gradients (apparent heat flow) in two deeper wells at 0.3 km depth (wells in column 30, see Fig. 1) and one well near the boundary of the inner hexagon (2R8, see Fig. 3).

Since the reservoir has not been exploited yet, the permeability structure could not be refined by matching any pressure response. We also neglected to match the observed concentration of chemical constituents in the thermal fluids since no geochemical data of unmixed deeper fluids are available.

Using the overall permeability structure of Hu (1989), we obtained a good fit model which provides acceptable fits for the three matching parameters listed above. The permeability structure of this model is shown in Fig. 5; computed temperature profiles for inner (column OA), and outer (column OB in Fig. 3) reservoir are shown in Fig. 4. This model transfers about 9.4 MW heat in the natural state involving an upflow rate of (unmixed) deeper fluids of about 24 kg/s at a level of -160 m. It also produces temperature gradients at 0.3 km depth in the three deeper wells which are close to the observed values (Fig. 6a).

For the simulation, it was assumed that the permeability of all blocks was initially zero, and that at time t=0 the permeability structure shown in Fig. 5 was created. The initial crustal temperature field was that produced by a constant terrestrial heat flow of 75 mW/m^2. The model was run until stable temperature and stable flows were reached in the natural state. We were not happy with the result that the Zhangzhou system could be modelled by using almost the same permeability structure as that derived previously from modelling the Fuzhou system. Hence, we undertook a sensitivity analysis by changing, stepwise, the permeability of the major crustal rock units by up to one order of magnitude. The results of this analysis are summarized in Table 1.

TABLE 1:
Computed matching parameters (Zhangzhou catchment) resulting from stepwise modification of the best fit model (Fig. 5)

Changes	Best fit model	<——— Best fit model parameters ———>				
	120° 9.4 38.5	Unit 1 (1 mD)	Unit 2 (0.5 mD)	Unit 3 (0.1 mD)	Inner reservoir (100 mD)	Const. heat flow at bottom (75 mW/m^2)
Unit 1 (5/0.5 mD)		119°/116° 10.4/9.5 33.5/38				
Unit 2 (2/0.1 mD)			104°/66° 10.4/1.9 18/49			
Unit 3 (0.25/0.05 mD)				109°/112° 8.3/8.7 28/42		
Inner reservoir (400 mD)					111° 8.3 37.5	
Heat flow decreasing with depth (see text)						116° 8.7 42

Selected computed matching parameters are listed in a three-figure vertical array:

1st figure: temperature in inner reservoir at 0.11 km depth.

2nd figure: anomalous heat loss of Zhangzhou prospect (in MW).

3rd figure: apparent heat flow (mW/m^2) at 0.3 km depth in deep wells in high terrain (column 30 in Fig. 1).

It can be seen from this table that changes in the equivalent overall permeability of rocks in unit 1, i.e. all exposed rocks down to a level of -0.56 km, has little effect upon the overall fit. Our adopted mean permeability of 1 mD (10^{-15} m^2) for the whole terrain is the same as that used by Forster and Smith (1988), who have modelled groundwater flow systems in mountainous terrain; they found that groundwater levels are significantly depressed (with respect to the surface level) if the terrain permeability exceeds this value. The water level in the two deep wells in our model is not much depressed (–10 m and –50 m for well ZK 3101 and ZK2401 respectively). The fluid flow pattern is controlled more by the overall permeability of the next, deeper unit 2, i.e. rocks between a level of -0.56 to -5.1 km depth, where most of the heat is extracted by deep radial fluid sweeps. There is an indication that the permeability of this unit in the best fit model (0.5 mD) is an optimum value. If the permeability of this unit is much lower, the sweep flow is too low to produce sufficient ascending fluids. If the permeability is higher than 0.5 mD, then cooling of the rocks in the upper unit becomes significant in the whole catchment.

Since there is not much heat extracted by deep sweeps in the lowest rock unit, i.e. rocks between a level of -5.1 to -9.1 km, changes in the overall permeability of unit 3 also produce little effect. However, the deepest layer cannot be neglected since the temperature gradient in the outer, higher terrain increases if the deepest layer becomes impermeable. In the best fit model, the total fluid flow in unit 3 is still one third that in unit 2. The data in Table 1, however, show that a large number of models can be constructed which all provide acceptable fits.

Implications of the Zhangzhou model

As can be seen from the previous discussion, we were more interested in assessing the effects of terrain-induced, forced convection upon the temperature and fluid flow pattern beneath the whole Zhangzhou catchment than obtaining a detailed model for the Zhangzhou geothermal reservoir. The best fit model presented here shows that the temperature field beneath the whole catchment is disturbed by secular convection which might extend throughout the whole upper crust. Most of the higher terrain acts as a recharge area, whereas discharge is mainly concentrated in the Zhangzhou Basin and within the broad valley systems lying to the NW and NE of the Zhangzhou prospect.

The recharge and discharge areas can also be recognized from the magnitude and direction of computed vertical flowrates (normalized for a unit area of 1 km^2) which are plotted for three radial profiles in Figs. 6a, b and c. Good correlation exists between computed (and observed) temperature gradients at 0.3 km depth and the direction of vertical fluid flow; temperature gradients of less than 0.03°C/m are typical for downflow (recharge) areas, and gradients higher than 0.03°C/m can be observed in discharge areas. Since there is also significant horizontal crossflow, there is no linear relationship between the two.

The conceptual model of the Zhangzhou system is probably biased by our attempt to fit temperature and heatflow data in two deeper wells in column 30 (Fig. 1) of the model. However, the finding that anomalously low temperature gradients (≤0.015°C/m) have been found in deep wells in higher terrain surrounding other coastal catchments in Fujian Province indicates that our model has some merit, although it is not sufficient to describe local details.

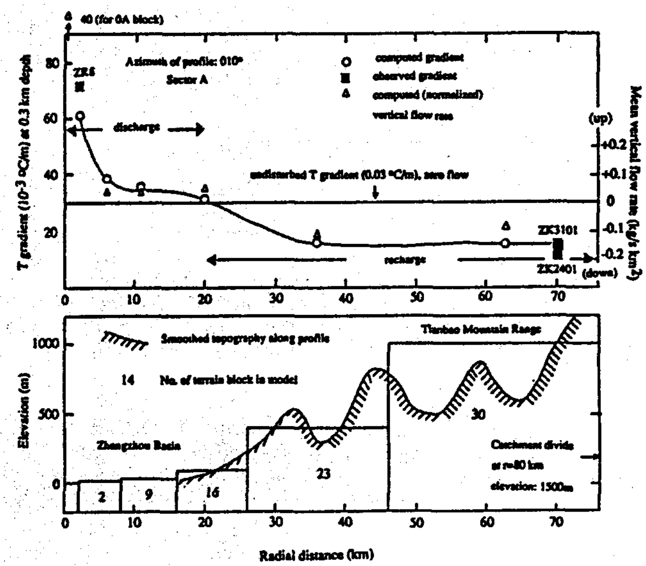

Fig. 6a: (Upper part) Computed (and observed) temperature gradients at 0.3 km depth along a radial profile in sector A (azimuth = 010°) through the Zhangzhou Catchment; shown also are the computed natural, vertical flowrates (kg/s/km^2) for each column at a constant level of –0.16 km. The apparent vertical heat flow can be obtained from the gradients by allowing for a mean thermal conductivity of 2.6 W/m°C.
(Lower part) Mean elevation of surface blocks along the same profile and smoothed topographic contours (taken from a 1:750000 topographic map of Fujian Province).

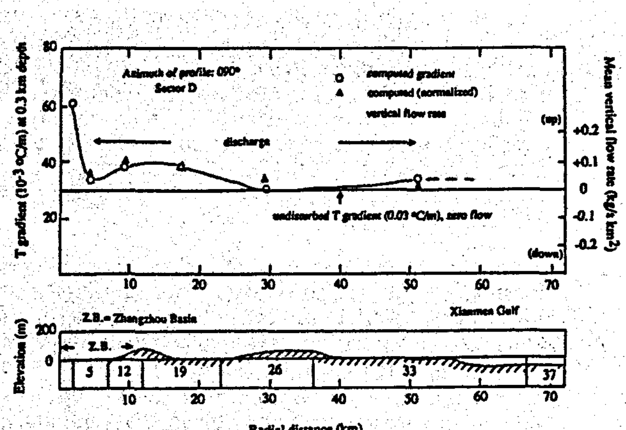

Fig. 6b: Temperature gradient, normalized vertical flowrate and topographic section for a radial profile in sector D (azimuth = 090°); for details see caption of Fig. 6a.

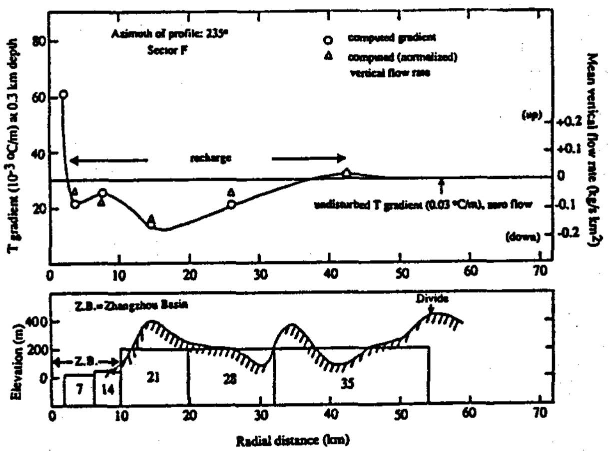

Fig. 6c: Temperature gradient, normalized vertical flowrate and topographic section for a radial profile in sector F (azimuth = 235°); for details see caption of Fig. 6a.

Our study indicates that it is impossible to assess the magnitude of the terrestrial conductive heat flow in a large catchment from a set of temperature profiles and thermal conductivity measurements in a number of deep wells. We have used the term "apparent heat flow" in the paper to emphasize this particular problem. Other modelling studies of heatflow data in basins (summarized in Wang and Beck, 1989) have produced similar results although they are based mainly on 2D models. Our studies (Fuzhou and Zhangzhou) have shown that the magnitude of the undisturbed crustal heat flow can not be assessed from modelling studies. In general, one can compensate any (reasonable) changes in heat flow at the bottom of these models by changes in their permeability structure if no restraints from very deep wells are available. Assuming an exponential decrease in the heat-generating capacity of granites in the Zhangzhou prospect, we modified the good fit model shown in Fig. 5 by assuming that these rocks extend down to unit 3, and that partial heat flows of 8.5 mW/m^2 and 7.5 mW/m^2 are produced within unit 2 and unit 3 respectively which reduce the heat input at the bottom of unit 3 to 59 mW/m^2. The results of this model are shown in Table 1.

If one looks at the overall heat and mass transfer beneath the whole Zhangzhou catchment as given by the good fit model, it was found that most of the anomalous heat (about 100 MW) swept from deeper crustal layers is transferred to blocks beneath broader valley systems in sector B (columns 3, 10, 17, 14) and sector G (columns 29, 22, 1, 5, 8). Only 10% of this heat is discharged by the Zhangzhou fracture zone system.

In the widest sense, the whole Zhangzhou catchment constitutes a "geothermal system" where most of the heat is transferred to the surface by secular fluid flow (our model indicates that in most blocks upward flow is not greater than 0.15 $kg/s/km^2$) which involves fluid temperatures which are only slightly greater than temperatures in a crust heated by conduction only. We propose the term "regional catchment system" to describe the regional and heat and mass transfer which most likely occurs beneath the Zhangzhou catchment. If deep-reaching, permeable basement fractures exist, low temperature fracture zone systems (Hochstein, 1988) can develop locally within a regional catchment system. Within the regional Zhangzhou (parent) catchment system, the Zhangzhou thermal prospect is such a local low temperature (daughter) system.

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