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CONCEPTUAL MODEL AND ASSESSMENT OF THE YANGBAJING GEOTHERMAL FIELD, TIBET, CHINA

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ABSTRACT

The Yangbajing geothermal system in Tibet, China, is characterized by a deep and hot vertical upflow zone, which is feeding a shallow and horizontal outflow zone. The deep part has a measured temperature of 250-320°C at 1000-2000 m depth. One well there is already tapping the equivalent of 10 MWe from this volcanic and vertically fractured reservoir. Hot fluid ascends to shallow depths where it turns laterally towards the south-southeast, within the sedimentary, 150-170°C, shallow system, at 180-280 m depth. Hot springs and thermal lakes finally discharge the geothermal fluid to surface. More than 54 wells have been drilled into the Yangbajing system, most are tapping the shallow reservoir only. Electrical generation, which began in 1976, has led to pressure drawdown in the shallow system and a substantial land subsidence. Furthermore, the drawdown has initiated recharge from the system outer boundaries that in turn has cooled down some shallow wells to the south. On the other hand, some shallow wells in the north have become hotter due to increased fluid recharge from depth. The shallow reservoir may cover as much as 15 km^2 while the deep system is considered less than 4 km^2 in area extent.

A simple 3-D numerical TOUGH2-EOS1 model has been developed for the Yangbajing system. At present it is only capable of simulating coarsely the initial reservoir temperature distribution, using 1176 rectangular elements in 7 horizontal layers and 6 rock types. Permeability in the vertical upflow zone was estimated near 20 mD and in the horizontal shallow system as high as 250 mD, while the outer model boundaries range from 0.1 to 5 mD. The model is heated with a deep, 330°C hot inflow of 25 kg/s.

1. INTRODUCTION

The simultaneous exploration and exploitation of the Yangbajing geothermal field were initiated in 1976 (Chen Xinji and Wang Zirui, 1981). A geothermal power plant with a capacity of 1 MW electricity started producing in 1977. At present, the total capacity has increased to 25 MWe. The power plant consists of two units. Both use a shallow reservoir for production. The power plant has not generated at full capacity for several years. The main reason is a decline in temperature and pressure in the shallow reservoir. However, the temperature in a few wells in the northern part of the well field increased with production. This indicates that a hot recharge is taking place in the shallow reservoir. The fraction of thermal water, which presumably comes from a deeper reservoir, has increased. A deep heat source was therefore considered to be located in the northern part of the field.

Exploration of the deep reservoir started in the early 1990s. So far, three deep wells have been drilled in the northern part of the field. The reservoir temperature reached about 330°C in well ZK4002 at a depth of 1850 m. This is the highest temperature found in the Yangbajing geothermal field. Unfortunately, well ZK4002 showed unstable flowrates during the production test. Well ZK4001, on the other hand, obtained a stable flowrate of 84 kg/s during a 15-day discharge test.

Several geological and reservoir models have been put forward during the period of exploration in the Yangbajing geothermal field. Some descriptions of a geological model can be found in references (Dor Ji and Zhao Ping, 2000; Zhao Ping et al., 2000). In this paper, the existing data sources are revised in order to come up with a conceptual reservoir model. The present wellfield is described and temperature profiles in wells are drawn. Based on these, both temperature cross-sections and maps are made. With the revised conceptual model at hand, a 3-D steady-state numerical model is put forward. Due to limited access to field data, only temperature data is considered for the modelling. Some general conclusions are drawn from this very simple modelling effort.

2. THE YANGBAJING GEOTHERMAL SYSTEM

2.1 Location and general description of the field

The Yangbajing geothermal field is located about 90 km northwest of Lhasa, the capital city of Tibet, at elevations ranging from 4280 to 4450 m above sea level (Figures 1 and 2). The mean annual atmospheric pressure is 0.6 bars-a and the mean annual temperature is 2.5°C with an extremely low winter temperature of -30°C. The annual evaporation rate exceeds precipitation; the evaporation rate is 2100 mm and precipitation is 256 mm (Liang Tingli et al., 1995).

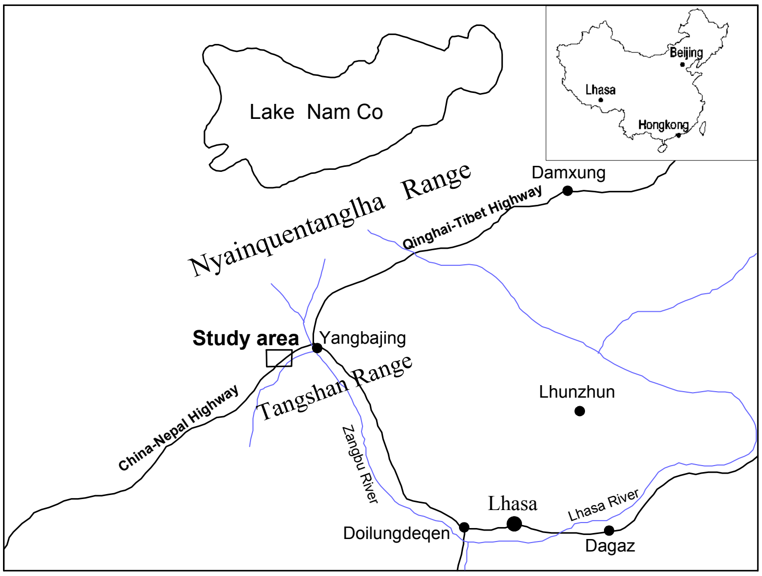

FIGURE 1: Location of the Yangbajing geothermal field

The Yangbajing geothermal field is located in a SW-NE trending Cenozoic basin generally called the Yangbajing basin. The basin is bordered by the Nyainquentanglha Range in the north and the Tangshan Range in the south (Figure 1). The basin is asymmetrical, i.e. the landform slopes gently in the northwest area of Zangbu River and steeply in the south (Figure 2). Several creeks have developed in the northwest area of Zangbu River (Figure 3). The Yangbajing geothermal field is considered the largest of several hydrothermal areas present in the basin. The China-Nepal highway crosses the middle of the field and divides the field into southern and northern parts. A shallow 150-165°C reservoir is observed in both parts. A deep reservoir is only found in the Northern part. It can be subdivided into two parts in the present wells at temperatures of about 250 and 300°C.

The first geothermal exploration began in 1976 in Yangbajing field. The study included geology, geophysics, geochemistry, drilling, well testing, etc. (Cheng Jiuxuan et al., 1984). A pilot geothermal power plant with 1 MWe capacity turbine ran successfully in September 1977. The installed capacity was increased to 25 MWe in 1991 and the annual power generation reached over 100 GWh. So far, only the shallow reservoir has been exploited for power generation, greenhouses, swimming pool and industrial uses such as boric mine processing.

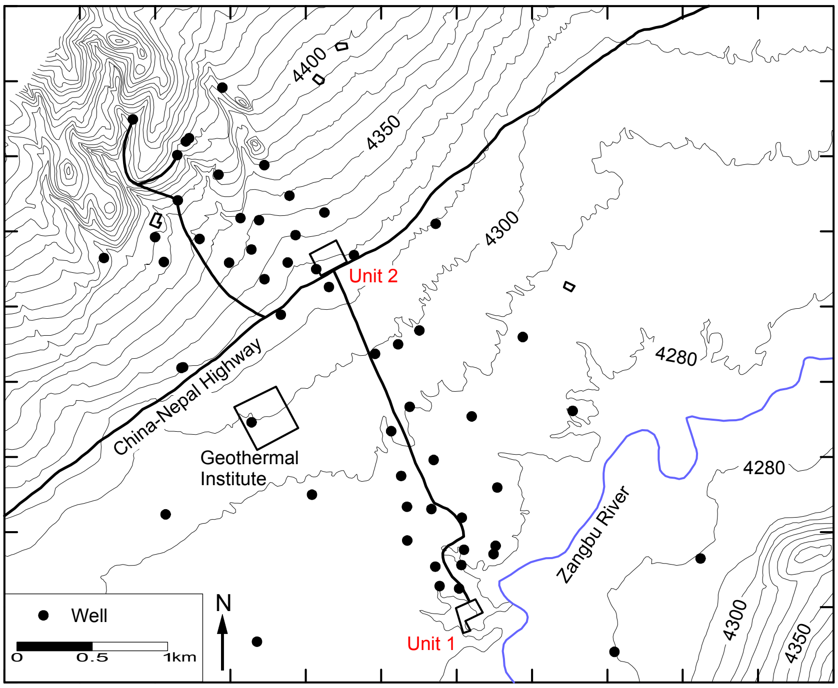

FIGURE 2: Topographic map of the Yangbajing geothermal field

Exploration of a deep high-temperature reservoir has been carried out since the 1990s. So far, three deep wells have been drilled in the northern part of the field. Well ZK352 was completed at 1003 m depth and reached a maximum bottomhole temperature of 202°C. This well just touched but did not expose the deep reservoir production zone. Well ZK4002 was drilled to a depth of 2006.8 m in 1993. It obtained a maximum temperature of 329°C. This is the highest temperature measured in the Yangbajing geothermal field. Unfortunately, it has unstable flowrates due to low permeability. Well ZK4001 was drilled to a depth of 1459 m in 1996. This well had a stable flowrate during a 15-day discharge test. Its wellhead conditions are 200°C, 15 bars and 84 kg/s. This well is expected to support 12 MW of electricity, but has yet to be connected to the power plant.

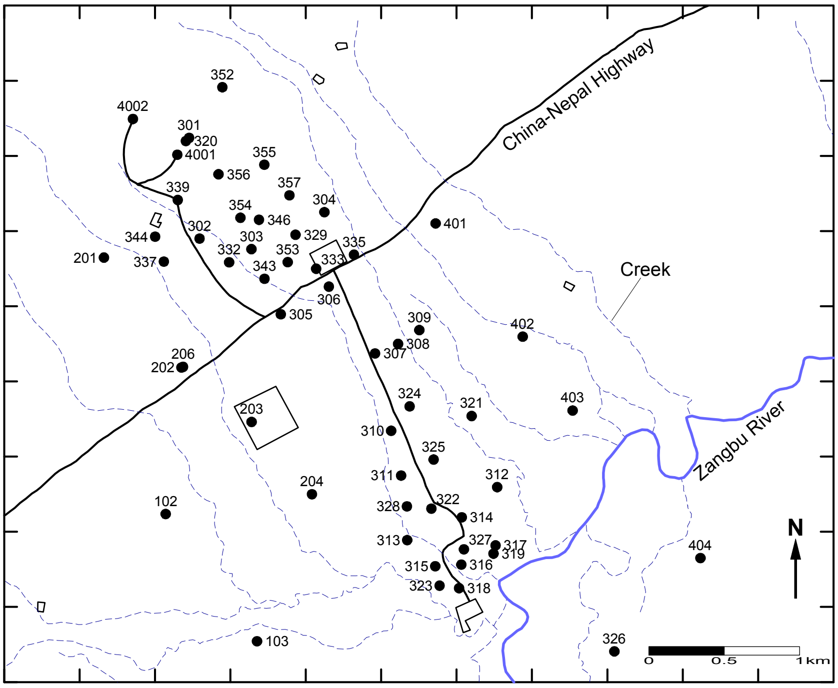

FIGURE 3: Well locations in the Yangbajing geothermal field

2.2 General geology

The collision of the Indian plate with the Eurasian plate resulted in the uplift of the Himalayas and formed the Qinghai-Tibetan plateau (Hochstein and Yang, 1992; Hochstein and Regenauer-Lieb, 1998). Tibet is located on the southern part of this plateau. The plateau consists of a series of terranes welded to each other by suture zones (Dor Ji and Zhao Ping, 2000). From a tectonic viewpoint, the Tibetan plateau is composed of four terranes and three E-W striking suture zones.

There is a suite of basins southeast of the Nyainquentanglha Range. The basins make a belt zone that is spreading NE-SW. The Yangbajing basin is one of the largest basins among the active NE-SW striking tectonic zones. It is bordered by Tangshan Range in the southeast and the Nyainquentanglha Range in the northwest. Faults developed at different stages; they are arranged in steps and incline from the basin border toward the centre. Faults scarps and terminal facets developed along fault lines and cluster directionally. Displacement of graben subsidence is in the range of 200-300 m. Tectonic activity is intense in the basin (Figure 4). The Quaternary till sheet step is sheared by NE-SW striking faults and recent alluvium has been telescoped since the end of the Cenozoic Era. There were 30 earthquakes of magnitude 4.75 or greater between 1921 and 1991, demonstrating ongoing tectonic activity in the Yangbajing geothermal field (Dor Ji and Zhao Ping, 2000).

The Yangbajing geothermal field is adjacent to the Gangdise volcanic arc in the south and the Nyainquentanglha Range core complex in the north. The high-temperature centre of the field is situated in the hanging wall of the slip-fault zone where thermal fluid upwelling occurs. The southern part of the geothermal field is covered by widespread Quaternary alluvium, while the basement is Himalayan granite and tuff. The northern part of the field is underlain by Quaternary alluvium and altered Himalayan granite over dense granite and the Nyainquentanglha core complex. Shallow strata are intensively altered and often replaced by kaolinite. NE-SW and NW-SE striking tensional faults have created a rhombohedral structural fabric (Figure 4).

The shallow reservoir is hosted by porous Quaternary alluvium in most part of the field except for a small area in the Northern part where the host rock is composed of altered Himalayan granite. The shallow reservoir is located beneath variable thicknesses of pelitic conglomerate or silty clay in Quaternary conglomerates, glacial sandy-gravel and weathered granite. The basement rock is Himalayan granite. Tuff Mylonitized granite is locally present in the northern part of the field (Dor Ji et al., 1996).

Yangbajing field is located where the strike of the Nyainquentanglha lateral fault zone changes from N60°E to N30°E. At Yangbajing the tectonic stress is concentrated and the fractures are more developed. The fractures consist mainly of two groups of faults namely northeast striking ones and northwest striking ones that intersect each other to make rhombic block structures (Figure 4).

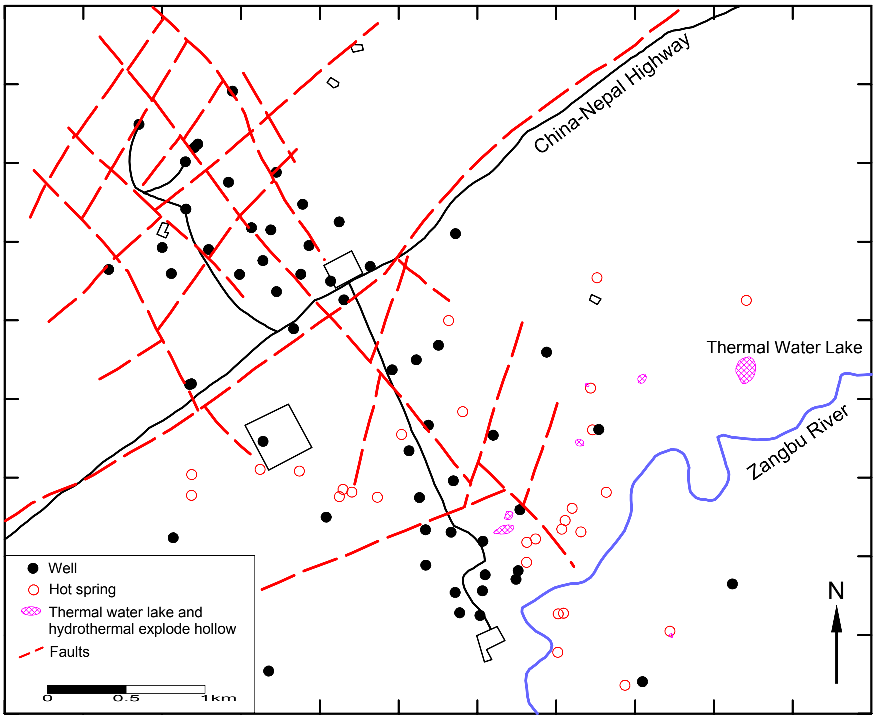

FIGURE 4: Tectonic and geothermal manifestation map

Ten northeasterly striking faults are recognized by field observations and drilling. One of them is located at the boundary between the northern and southern parts of the field. Five of them are in the Northern part, and four in the Southern part. Four northwesterly striking faults are also recognized which stand side by side and parallel at almost the same 500 m intervals. The second one from northwest may possibly reach up to the Zangbu River. If this is the case, the ascending flow from depth in the Northern part turns to a lateral direction at shallow depths, and then the geothermal fluid may flow along this fault to the south.

The shallow reservoir is porous medium seated in Quaternary alluvium in the Southern part, and in alluvium and altered Himalayan granite in the Northern part. The shallow reservoir in the Southern part is very shallow and not thicker than 100 m. The shallow reservoir in the Northern part is seated below the depth of 150 m, and is less than 200 m thick (Dor Ji et al., 1996). The mean porosity in the Quaternary alluvium is 15 – 20%. As mentioned earlier, the deep reservoir in the North is, on the other hand, fracture dominated and hosted in volcanic formations.

2.3 Exploration and production history

A reconnaissance survey of possible porcelain clay and sulphur mines in Yangbajing was underway before 1973. A geothermal reconnaissance survey began in 1974, including gravity, electrical and magnetic surveys. A more intense investigation of geothermal energy started in 1976, and resulted in the drilling of 42 exploration and production wells until 1984. During this period the main exploration target became the shallow reservoir of the field (Chen Xinji and Wang Zirui, 1981).

Between 1985 and 1991, based on the data obtained in the earlier studies, the exploitation of the shallow reservoir continued. New production wells had to be drilled in order to provide thermal fluid to the expanding power plant. Table 1 summarizes some basic parameters of most exploration and production wells in this field. Table 2 shows the output capacity of some of the production wells (Cheng Jiuxuan et al., 1984; Liang Tingli et al., 1995; Dor Ji et al., 1996).

Exploration of the deep reservoir began during the exploitation of the shallow reservoir. The first deep well (ZK352) was drilled in 1991 in the north area. Information of high temperature, 202°C, was obtained at a depth of 970 m. Since then, exploration of the deep reservoir has continued. These include geological surveys, geophysical surveys, gravity, resistivity, and magnetic surveys (Liang Tingli et al., 1995). Based on these data, two deep wells were sited and drilled in 1993 and 1996.

The initial electricity generation of the Yangbajing geothermal pilot power plant began in 1977 with a one MW turbine generator. The total capacity reached 25 MW when the last 3 MW turbine generator joined the electricity net in 1991. The amount of electricity generation increased along with an increase of the installed capacity and reached a peak in 1994, but has since been on a small but gradual decline (Figure 5). This behaviour has to do with the massive production out of the shallow reservoir. The cumulative amount of electricity generation of Yangbajing geothermal power plant is 1.364 TWh from 1977 to 2000.

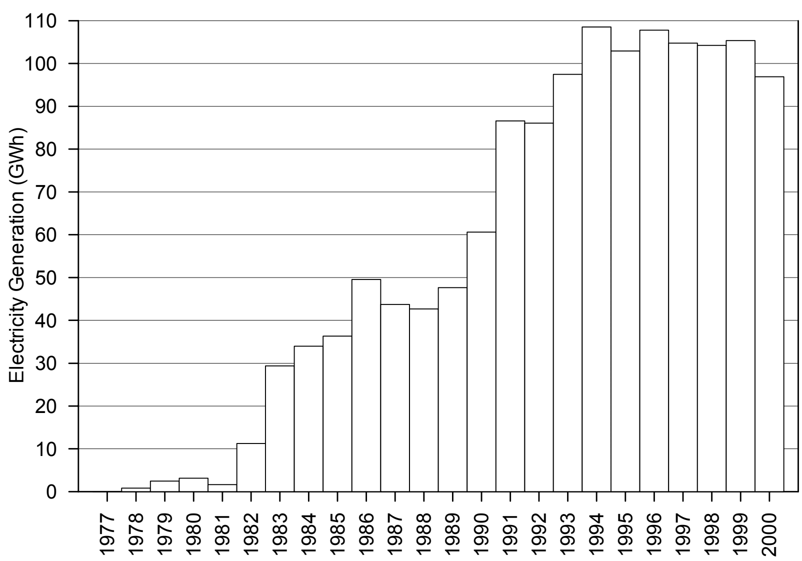

FIGURE 5: Electricity generation output of the Yangbajing geothermal power plant in the years 1977-2000; the amount in 1977 was 49.4 MWh

TABLE 1: General well information in the Yangbajing geothermal field

Well no. (ZK)	Well type	Drilling time	Well depth (m)	Casing depth (m)	Altitude (m)	Water level (m)	Quality
102	e	84.5.13 - 6.4	274.37	19.21	4290.96		good
103	e	83.5.26 - 7.19	366.33	87.37	4284.5		excellent
201	e	81.5.24 - 11.3	269.88	96.61	4404.55		discarded
203	e/p	77.10.17 - 12.1	457.28	255	4297.21	1.43	good
204	e/p	80.4.7 - 5.22	551.48	235.91	4287.1	-36.88	good
206			700.63		4316.32		
302	p	79.4.8 - 6.10	457.41	288.41	4352.98	45	excellent
303	e/p	79.7.9 - 7.31	336.27	268.45	4332.81	24.66	excellent
304	e/p	78.8.14 - 10.13	206.5	126.81	4333.86	25.25	good
305	p	79.5	203.29	202.44	4315.37	8.07	good
306	p	79.9.7 - 9.25	223.47	219.67	4310.31	0.39	good
307	p	79.8.29 - 9.24	341.97	241.46	4298.11		good
308	e	80.6.30 - 9.23	1726.41	483.34	4297.32	0.35	discarded
309	e/p	78.5.23 - 6.23	87.25	65.82	4298.02	-48.65	excellent
310	p	79.6.14 - 7.3	213.55	171.84	4290.61	-33.06	good
311	p	80.6.26 - 7.18	81.82	57.17	4286.37	1.6	excellent
312	p	80.7.26 - 8.21	225.2	160	4283.3	-29.17	good
313	p	78.8.4 - 8.27	155.4	149.59	4283.2	-33.16	excellent
314	e/p	78.9.30 - 11.19	354.77	236.77	4284.06	-37.86	good
315	p	77.8.20 - 9.19	68.42	68.42	4281.78	-35.71	excellent
316	e	75.7.1 - 9.2	42.59	37	4283.16		discarded
317	e	76.8.30 - 9.	74	36.39	4284.7		discarded
318	p	76.9.30 - 12.7	311.21	299	4283.77		qualified
319	p	80.6.1 - 6.23	156.93	126.15	4284.5	31.29	excellent
320	e	82.8.1 - 10.21	252.35	173.41	4427.26		
321	p	82.5.21 - 6.28	179.51	115.71	4286.6		
322	p	82.7.4 - 8.6	107.35	74	4283.02		exploded
323	p	82.8.20 - 9.19	131.97	131.53	4281.17		
324	p	82.9.27 - 10.21	90.13	81.28	4289.95		
325	p	84.7.18 - 8.5	94.5	70.57	4285.6		
326	e	84.8.23 - 9.17	172.32		4281.12		good
327	p	84.5.27 - 6.15	118	118	4282.23		
328	p	84.6.23 - 7.10	108	108	4284.06		
329			218		4328.16		
332			217.25		4342		
333			217.25		4317		
335			182.38		4319		
337			300.38		4368.08		
339			260.2		4371.5		
343			358.46		4325.06		
344			291.18		4375.2		
346			258		4334.92		
352			1003.39		4406.61		
353			301		4321.67		
354			272.7		4338.36		
355			454.18		4362.99		
356			610.69		4381.13		
357			402.89		4345.14		
4001	e		1459.09		4424.35	-150	
4002	e		2006.8		4429.12		
401	e	83.5.29 - 8.3	453.32	40.36	4308.39		qualified
402	e	84.5.22 - 7.9	263.64	81.73	4286.35		qualified
403	e/p	78.6.28 - 8.20	603.21	276.56	4279.7	1.83	qualified
404	e	84.7.19 - 8.14	221.22	92.34	4282.44		good

e - exploration well; e/p - exploration and production well; p - production well

TABLE 2: Output parameters of production wells in the Yangbajing geothermal field

Well no. (ZK)	Test time	Test method	Highest temperature in well (°C)	Well head temperature (°C)	Well head pressure (bar)	Lip pressure (bar)	Flowrate (kg/s)	Capacity (MWe)
203	79.7.12 - 13	LP (s)	141	125	2.2	0.7	23.8	0.82
204	81.7.30 - 31	LP (s)	147	122	2.2	0.7	21.2	0.77
302	79.7.13 -14	LP (s)	172	137	3.5	1	25.7	1.12
303	80.7.24	LP (s)	167	134	3.2	1	26.9	1.11
304	79.9.15 16	LP (s)	172	133	3.7	1	25.7	1.11
309	79.10.9 - 11	LP (m)	160	146	4.6	1.9	49	1.95
310	79.8.15 - 17	LP (m)	160	125	2.9	0.8	22.4	0.89
311	80.8.4 - 6	LP (m)	157	147	4.7	1.7	45.6	1.78
312	80.8.2 - 4	LP (s)	149	138	3.6	1.1	32	1.17
313	79.9.6 - 9	LP (m)	161	131	3.3	0.9	25.2	1.01
314	79.8.30 - 9.1	LP (m)	160	131	3.5	1.1	28.9	1.16
315	77.9.7	LP (m)	152	127	3.1	1.8	20.1	0.76
319	80.7.17 - 20	LP (s)	161	130	3.3	1.1	29.3	1.17
321	82.7.8 - 10	LP (s)	155	120	2	0.7	20	0.77
324	82.10.27	LP (s)	160	147	4.3	1.8	47.1	1.87
325	84	LP (s)	155	143	4.1	1.6	45	1.73
327	84	LP (s)	152	116	2.6	0.9	25.9	0.97
328	84	LP (s)	152	138	3.4	1.3	38.1	1.43
329	85.10.2 - 11.6		165	130	3	1	26.1	1.04
332	85.5.9 - 5.13		165	130	2.6		22.2	0.8
346	88.6.11 - 6.23		169	134	3.2	1	26.1	1.06
352	87.10.10		202	116	1.8	0.9	18.8	0.94
353	90.7.21 - 8.10		165	123	2.9	0.9	23.6	0.94
354	90.9.15 - 10.14		173	144	3.3	1	24.8	1.04
355	91.5.14 - 6.15		173	123	2.3	0.8	20	0.84
356	91.7.19 - 9.7		171	125	1.8	0.7	17.8	0.74
357	91.9.15 - 10.8		162	126	2.3	0.8	23	0.89
330	84.8.21 - 9.15		165	132	2.7		26.4	0.95
331	84.9.22 - 9.29		165	130	3.1		23.6	0.95
333	85.6.1 - 6.5		165	133	3.4		29.4	1.15
4001	96.10.30 -	LP (s)	250	195	15	5	83.5	12.5

LP (s): lip pressure method, single-well discharge; LP (m): lip pressure method, multi-well

3. ANALYSIS OF TEMPERATURE DATA

In this chapter, some general conclusions regarding the temperature distribution in Yangbajing are described. The work consisted of siting the wells on a map, finding downhole temperature profiles in existing literature and plotting them with respect to elevation. Based on these, several temperature plane sections are made.

3.1 The shallow reservoir

The shallow reservoir has an area of about 14.6 km^2. When drilling, it is generally found between the depths of 180–280 m below surface. Its temperature ranges from 150 to 160°C. The highest measured temperature in the shallow reservoir wells is 173°C. Historically, the shallow reservoir is divided by the China-Nepal Highway into Southern and Northern parts.

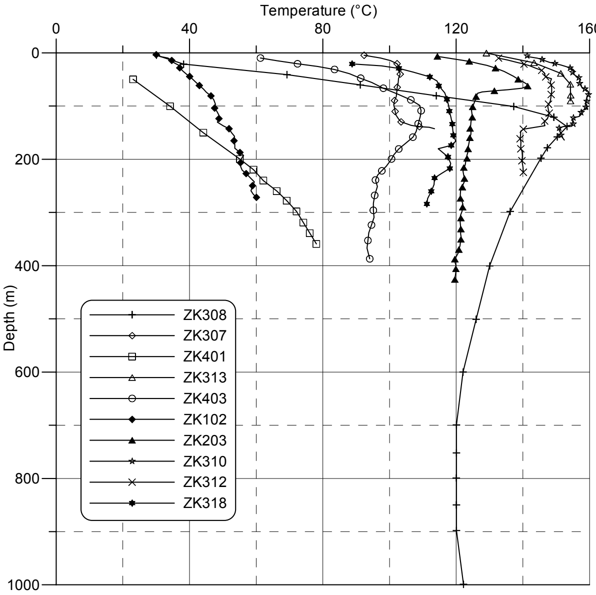

FIGURE 6: Downhole temperature profiles in shallow reservoir wells belonging to the South field

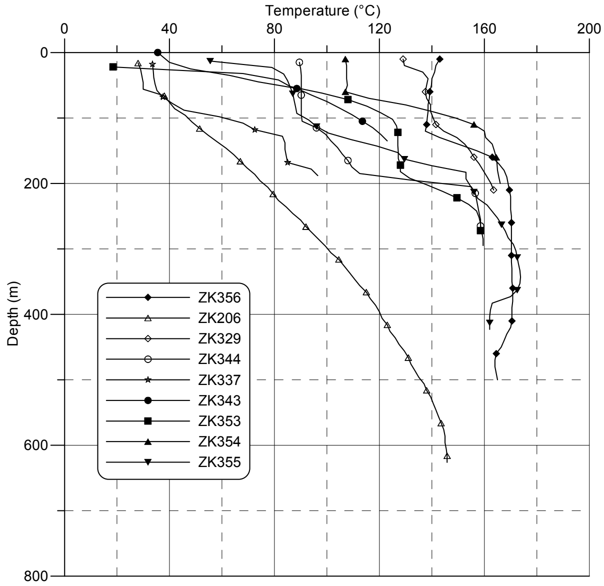

FIGURE 7: Downhole temperature profiles in shallow reservoir wells belonging to the North field

The temperature in the Northern part is generally higher than in the Southern part. The temperatures in most wells in the Southern part are reversed with depth (Figure 6). The temperatures in most wells in the Northern part, on the other hand, increase with depth (Figure 7). This has been interpreted as upwelling of thermal water in the Northern part, and lateral flow of thermal water to the southern shallow reservoir.

Figures 8, 9 and 10 show temperature contour maps at 4300, 4200 and 4100 m a.s.l. Most important here are two consistent features, 1) a high-temperature zone to the northwest, and 2) a NNW-SSE trending temperature anomaly, parallel to one of the faults shown in Figure 4.

Due to the limited downhole temperature data available for this study, it is of interest to draw only the maximum observed temperature in the shallow Yangbajing wells. This is shown in Figure 11. The same conclusion can be drawn here as from Figures 8-10, i.e. a high-temperature anomaly to the northwest and a south-southeast striking outflow zone.

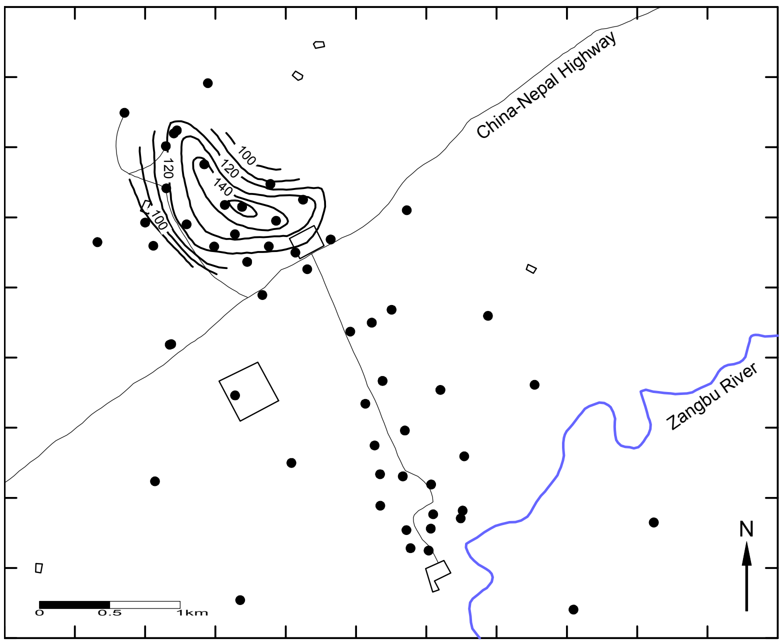

FIGURE 8: A temperature contour map (°C) of the shallow reservoir at 4300 m a.s.l.; wells are shown by black bullets

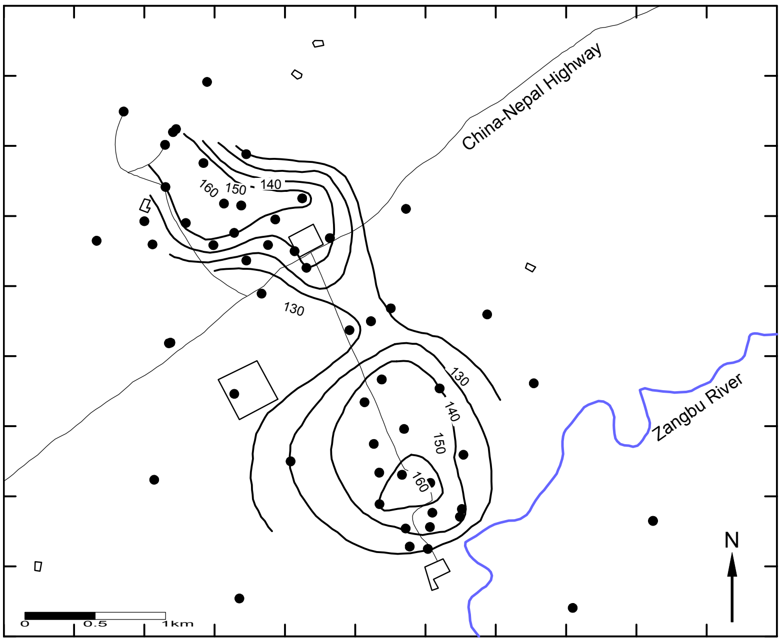

FIGURE 9: A temperature contour map (°C) of the shallow reservoir at 4200 m a.s.l.

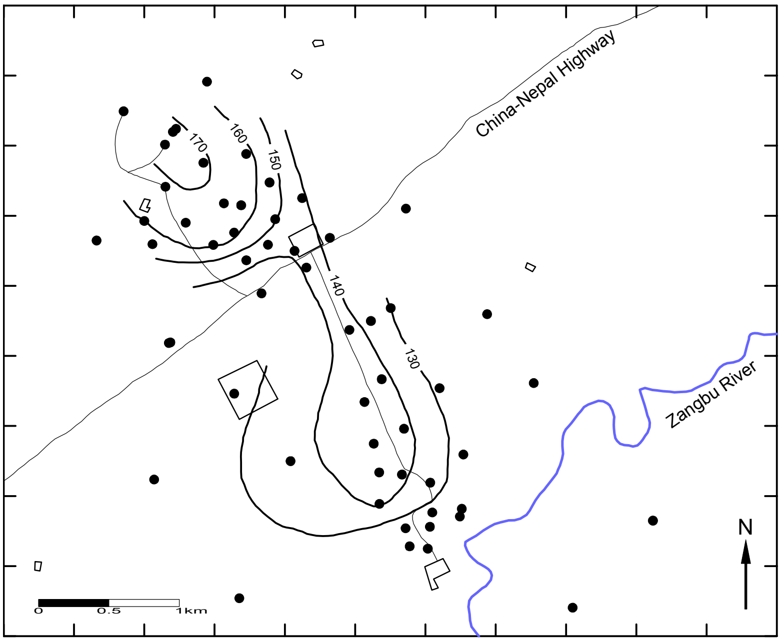

FIGURE 10: A temperature contour map (°C) of the shallow reservoir at 4100 m a.s.l.

3.2 The deep reservoir

As mentioned earlier, since 1992 some geological, geophysical and geochemical surveys and logging data already indicated the presence of a deep geothermal reservoir in the Northern part of the Yangbajing geothermal field (Liang Tingli et al., 1995). Recent exploration drilling has proven the presence of a deep high-temperature reservoir zone. Both the shallow and the deep reservoirs belong to the same hydrothermal system. They are distinguished depthwise by different temperatures. So far, only three deep wells have penetrated into the deep high-temperature reservoir. Figures 12 and 13 show downhole temperature measurements in wells ZK4001 and ZK4002, respectively. The figures show that the deep high-temperature reservoir consists of at least two layers. An upper layer with a temperature of 250–275°C is at the depth range 950–1350 m. The deeper layer has a temperature greater than 300°C and is found below the depth of 1500 m.

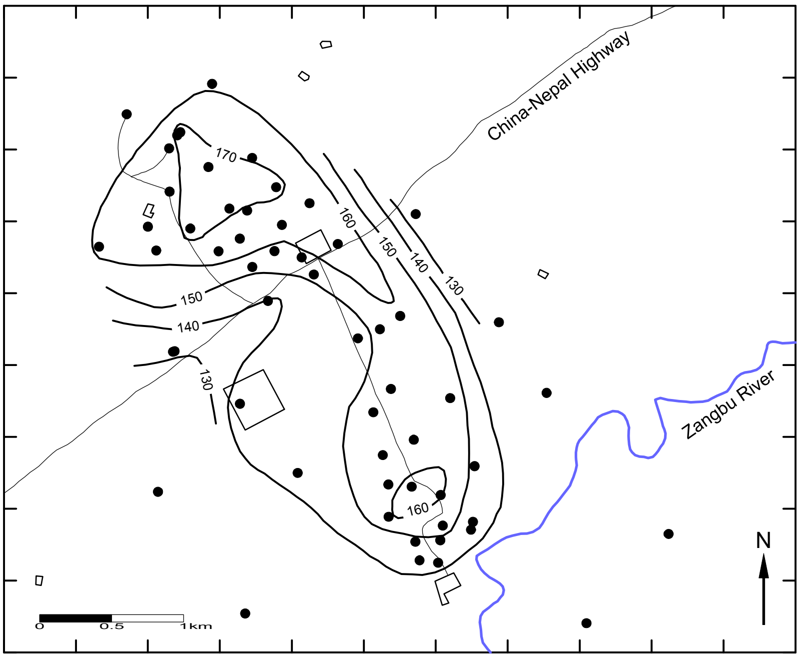

FIGURE 11: Isothermal contour map showing the highest measured temperature (°C) in wellbores of the shallow reservoir

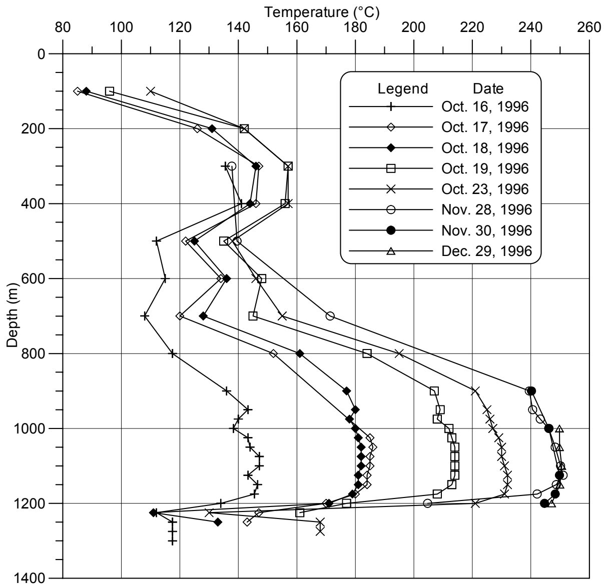

FIGURE 12: Temperature profile diagram of well ZK4001

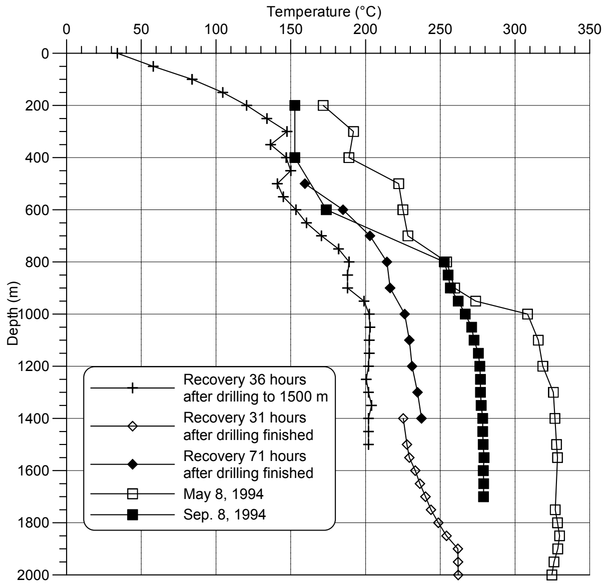

FIGURE 13: Temperature profile diagram of well ZK4002

The hotter well, ZK4002, had no stable flowrate and wellhead conditions during a discharge test. The temperature, pressure and flowrate declined rapidly. Its initial wellhead conditions were temperature of 204°C, pressure of 16.6 bars, lip pressure of 6.6 bars, flowrate of 67 kg/s. After 40 hours, it only produced dry steam and wellhead conditions were 135°C, 2.2 bars, lip pressure of 0 bar and steam flowrate of 3.3 kg/s. It stopped flowing after 15 days but produced again after 5–7 days rest (GGTT, 1995).

Well ZK4001 was completed in October 1996. The flowrate of ZK4001 quickly stabilized in a production test in 1996. Temperature and pressure increased slightly during the 15-day long discharge test. Wellhead conditions were 200°C and 15 bars with two-phase fluid at a flowrate of 84 kg/s and enthalpy of 1071 kJ/kg. The well is expected to produce 12.5 MWe. A maximum temperature of 255°C was recorded at 1125 m depth in 1997. The initial water level was 72 m in ZK4001 and 85 m in ZK4002. The water level of ZK4002 declined by 12 m during the 15-day discharge test of well ZK4001 (Dor Ji et al., 1996). It demonstrated that both wells are in the same hydraulic system and that the wells are connected to each other.

The deep reservoir area extent is expected to be in the range of 3.8 km^2 below a depth of 750 m. It appears to be a typical fracture-dominated geothermal reservoir. The location of the deep reservoir and migration of the deep thermal water appears strictly controlled by the faults in the region. The thermal water is stored in fracture zones and tectonic fissures in the rocks. The deep reservoir is found within mylonitized granite, granitic mylonite, and fractured granite that has characteristics of both ductile and brittle shearing.

4. ANALYSIS OF PRODUCTION DATA

So far the geothermal power plant has only relied on the shallow reservoir for electricity generation. Wellhead conditions during flow are normally 125–140°C and 1.8–3.8 bars. The pressure has declined in the production wells during exploitation. The temperature has also declined in most wells during the exploitation history. In some wells in the Northern part of the field, comparison of the temperature monitoring and previous logging data show increased downhole temperatures during production (Figure 14, Table 3). However, these did not exceed the highest temperature measured in the Northern part (Du Shaoping, 1991).

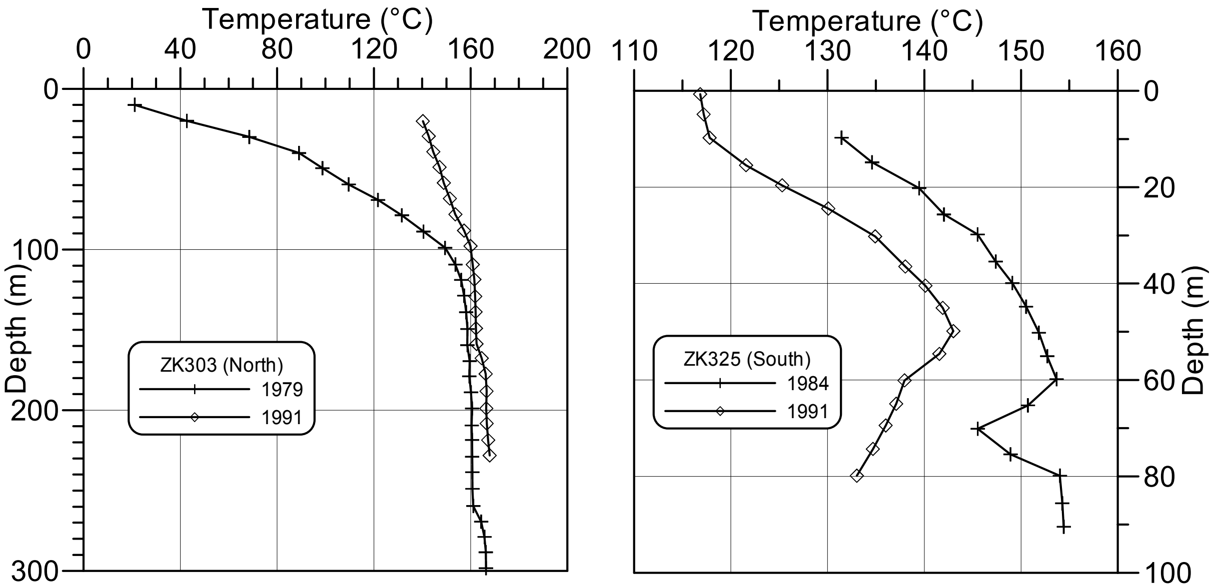

FIGURE 14: Temperature changes during production in two shallow reservoir wells, one belonging to the Northern field (left) and the other to the Southern field (right)

TABLE 3: Temperature changes during production in shallow reservoir wells

Well	Duration	Temperature	Location
321	82.6.30 - 83.9.9	-8	South
313	79.10.31 -	-6	South
308	82.6.4 - 83.9.10	-12	South
307	79.10.13 - 84.6.4	-7	South
319	80.6.27 - 83.8.21	-4	South
323	83.9.2 - 86.6.6	3	South
202	83.9.8 - 84.6.11	1	North
306	82.8.27 - 83.9.8	10	North
303	82.8.27 - 83.9.7	10	North
320	82.10.25 -	2	North
201	82.9.3 - 84.5.23	9	North

Subsidence is one of the responses to the exploitation in the shallow geothermal reservoir. The monitoring of ground surface subsidence and a high-accuracy gravity survey were carried out during 1983 and 1994. This work has been stopped due to lack of financial support. There is a subsidence centre in the southern part of the field (Figures 15 and 16). The greatest subsidence is more than 360 mm between 1983 and 1993. The annual mean subsidence is more than 35 mm/yr. These indicate a great mass loss of thermal water accompanied with the production as a consequence of the reservoir pressure drawdown and pore volume compression (Fan Xiaoping and Yang Zuhui, 1993).The ground surface in the northwest part, on the other hand, had a little uplift during the exploitation of the Northern field (Figure 16).

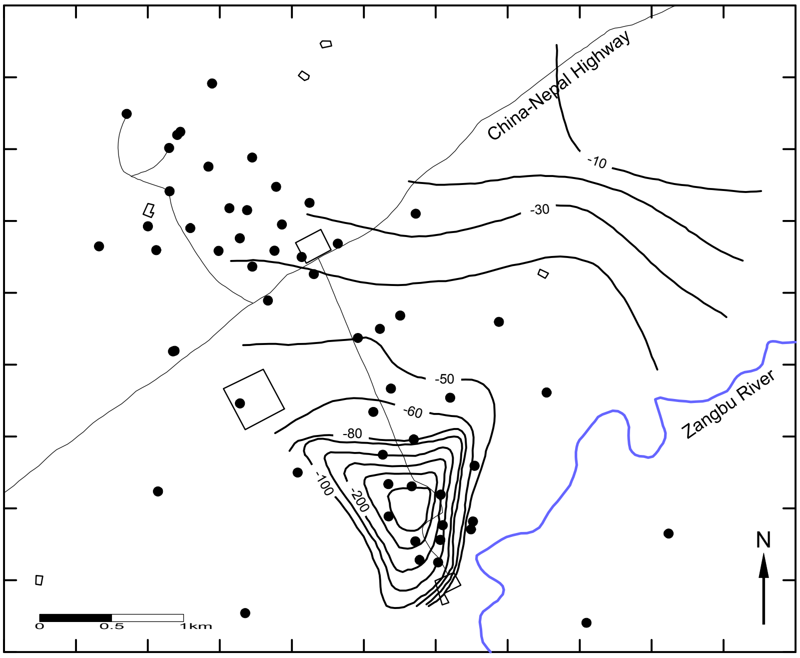

FIGURE 15: The ground surface subsidence in mm between 1983 and 1993

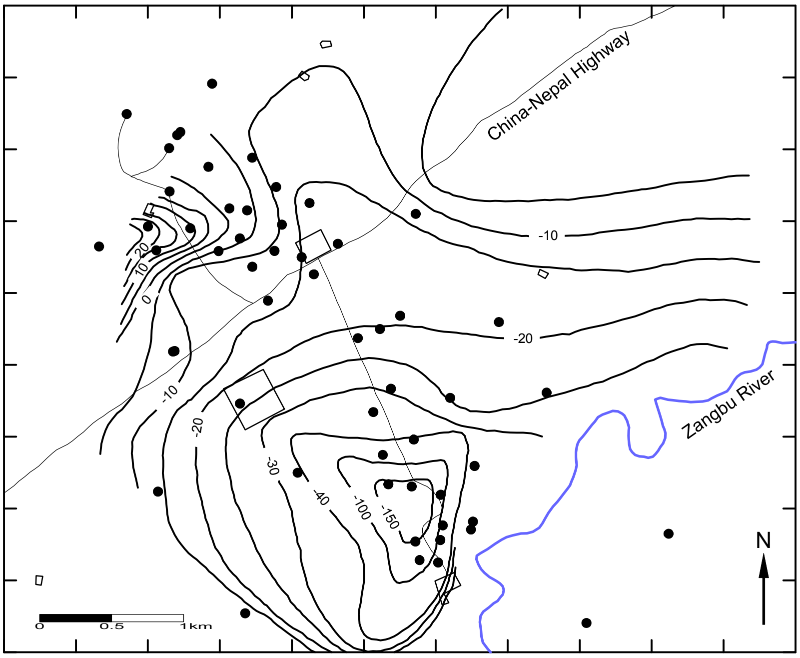

FIGURE 16: The ground surface subsidence in mm between 1989 and 1993

5. A CONCEPTUAL RESERVOIR MODEL

5.1 A large-scale model around Yangbajing

There is suite of basins present southeast of the Nyainquentanglha Range. These basins make a belt zone. There are also many fumaroles and hot springs in this belt. The basins are still developing by tectonic compressive stress, as the Quaternary formations are also deformed. There are some regions of sizeable geothermal manifestations in the belt. The Yangbajing is the largest among such regions. The distances between the adjacent basins are several tens of kilometres. And the basin belt is around 500 km long.

Nyainquentanglha Range started to develop from Eocene, and is still being lifted. The top of the range is around 20 km to the northwest of Yangbajing. The summit of the Tangshan Range is located around 15 km to the south of Yangbajing.

There are some geothermal manifestations around Nyainquentanglha Range, but not seen around Tangshan range. Heat sources are thought to be related to Nyainquentanglha Range. Each geothermal system may have a separate heat source. From late Cretaceous to Eocene, the ocean crust of Tethys Sea dove under the Eurasian plate to generate large-scale magma activities and the main body of Gangdise intermediate-acid rock. Later, in Eocene, the Indian continent collided with the Eurasian continent to make subduction weaker, and the magma activities reduced in spatial scale to make many small acid rock intrusions. With respect to Yangbajing, the depth of the heat source body is estimated at around 5 km below the northern part. There may be a variation of depths to the heat source bodies in the wide area along the Nyainquentanglha Range.

In Yangbajing, we have permeable formations at shallow depths. They are Quaternary formations. Also, we have permeable conduits at 950–1,336 m depth in well ZK4001. Similar conduits may be expected in a wide region along the Nyainquentanglha Range and the belt, so that extensive permeability may possibly be expected. The slippage of the faults may define some parts of the heat source to the geothermal systems. Possibly, heat source bodies and locations may control the geothermal convections as much as the permeability distribution. Distribution of heat sources and distribution of basins may be affected by the tectonic deformations and stresses.

In the natural state, the total heat discharge flux out of Yangbajing is on the order of 600 MW with a geothermal manifestation area of 14.6 km^2 (Cheng Jiuxian et al., 1984). In the northern part of Yangbajing the heat flux estimated is around 230 MW, based on data collected after exploitation started (Liang Tingli et al., 1995). Recharge fluid originates from glaciers seated at the Nyainquentanglha Range. With respect to Yangbajing, a small portion may also originate from groundwater in the Tangshan range and rainfall. According to results of an isotopic survey, Lake Nam Co is not thought to be a fluid source.

5.2 Heat structure and temperature distribution of Yangbajing

A heat source body is estimated to exist under the northern part of the field. The depth to it has been estimated around 5 km. Also, the vertical length of it is estimated as over 10 km. Horizontal size is uncertain. The heat source may be partially melted. Its temperature is uncertain, but may exceed 600°C, if close to melting (Dor Ji and Zhao Ping, 2000).

So far, two deep reservoir layers are confirmed by drilling. They have been related to major faults. The temperature at 1,100 m of ZK4001 is about 250°C, while temperature at 1,850 m of ZK4002 is about 330°C. The temperature at 1,000 m of ZK4002 is about 308°C. These indicate some temperature heterogeneity in the upper reservoirs layer, which supports flow in vertical fractures.

The temperature of the shallow reservoir is clearly lower than the deep reservoir and has variation according to location. The centre of highest temperature is identified around wells ZK320, ZK355, ZK357 and ZK302 in the Northern part (Figure 11). The highest measured temperature in the Northern part is 173°C ZK354, and in the Southern part, 161°C in wells ZK314 and ZK313 (Figure 11).

In the Southern part, almost all wells have reversed temperatures. Some northern wells also have the same situation. These temperature reversals may indicate low-permeability rock under the reservoir and heat transfer by conduction. There is a thermal water lake and some hot springs in the Southern part. These are hydraulically connected to the shallow reservoir, as observed by reduced activity after the start of exploitation. There may be some dominant conduits that connect the hot area of the shallow reservoir to the thermal water lake.

There are cap rocks overlaying the shallow reservoir in both Northern and Southern parts, seen by a linear temperature increase with depth (Figures 6 and 7).

5.3 Conceptual model of Yangbajing

From an isotopic survey, it is thought that the Yangbajing geothermal fluid originates from meteoric water, and that the recharge areas are zones at 4,400 to 5,800 m a.s.l., centred around 4,860 m a.s.l. The top of Nyainquentanglha Range exceeds 6,000 m a.s.l., and the range is covered by glaciers. It is thought that the melted water and rainwater at the foothills are the main origin of the geothermal fluid, and this meteoric water infiltrates through Nyainquentanglha Mountain's south edge faults belt. Also, according to the subsurface temperature distribution in the Southern part, Zangbu River and Tangshan may contribute part of the geothermal fluid.

Infiltrated meteoric water is gradually heated during its descent, and then makes reservoir fluid. Reservoir fluid is NaCl type in both the shallow and deep reservoirs. Chloride concentration is 1.5 g/l in the shallow reservoir and 2.8 g/l in the deep reservoir. The fluid in the deep reservoir ascends into the shallow reservoir where some mixing occurs with the cooler meteoric water.

Figure 17 shows the conceptual reservoir model of Yangbajing as defined by this study. An upflow zone

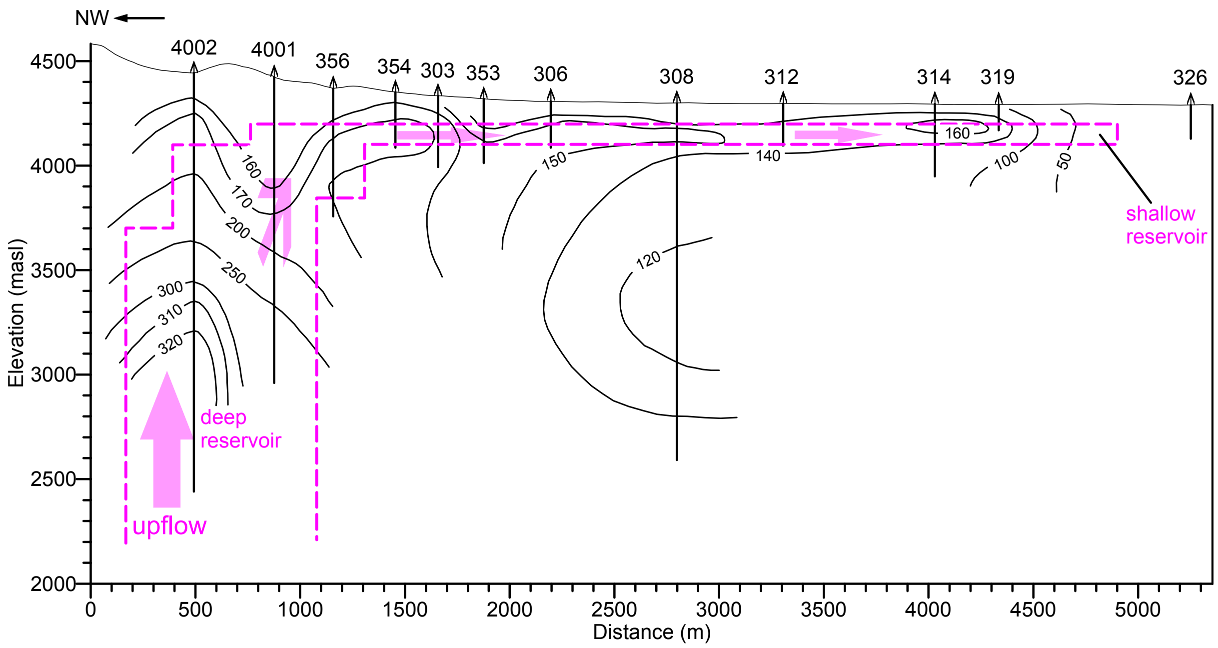

FIGURE 17: A conceptual model of the Yangbajing geothermal field, from north-northwest to south- southwest; wells are shown by their number on the surface

of the deep hot fluid is thought to be located in the Northern field. In there is an area with slightly lifted formations where thermal alteration is intensive and Quaternary formation removed. This lift of formation may be due to rock expansion by alteration. In general, the Northern part is more altered than the Southern part. There is other evidence of an up flow zone such as high anomaly of carbon oxide emission and higher temperature of the shallow reservoir in the Northern part than in the Southern part.

The conceptual model assumes that most of the ascending flow turns laterally at shallow depths, thus, making the shallow reservoir. Finally, the geothermal fluid flows up to the ground where the hot spring and thermal grounds are found near the Zangbu River. In the shallow reservoir of the Southern part, both the temperature and pressure tend to decrease from northwest to southeast. Tritium concentration data obtained after exploitation in 1993 indicates a fluid circulation time of 20 years. Spatial distribution of isotopic composition is regarded as showing flow direction from northwest to southeast in the Southern shallow reservoir.

The steam for electric generation has been obtained only from the shallow reservoir so far. Separated hot water was initially discarded to Zangbu River, while now around 70% is injected into the Southern shallow reservoir.

The temperature distribution in the shallow reservoir has changed due to exploitation. In the Northern part it became higher while in the Southern part it decreased. Wells that experienced temperature decrease are basically located at the margin of the field and in the whole Southern field. This suggests that the increase of lateral cold water supply due to large amount of fluid withdrawal from the shallow reservoir, caused the temperature decrease.

6. A NATURAL STATE 3-D NUMERICAL MODEL

With the conceptual reservoir model at hand, it is of interest to also set up a numerical model, in order to better understand subsurface heat and mass flow in the Yangbajing system. Numerical geothermal reservoir simulation is well known in the literature and many papers are available on the subject (Bödvarsson et al., 1984; Bödvarsson et al., 1986). Hu Baigeng (1993, 1995) developed a numerical model on the Yangbajing geothermal system, but assumed only one reservoir layer and did not include the deep reservoir. In the present simulation the conceptual model shown in Figure 17 is used as a basis. The conceptual model is only based on temperature distributions and is very simple. The hot water rises along a fracture zone under wells ZK4002 and ZK4001, then ascend to the shallow reservoir and moves laterally to the Southern field. Finally, some hot water comes out of the ground as hot springs, thermal water lake and fumeroles.

We assume that the Yangbajing geothermal system is in a dynamic equilibrium. That means the system is in a steady-state condition before production. The multiphase and multicomponent TOUGH2 simulation is applied here for the modelling (Pruess et al., 1999; Pruess, 2002). For simplicity, only the equation of state 1 is considered (pure water). Mesh is generated by using the TOUGH2 inbuilt meshmaker.

6.1 The model grid

Figures 18, 19 and 20 show the rectangular grid (mesh) applied to the present model. Figure 18 is a plane section showing the full extent of layer 2, where the Yangbajing well field is located in the centre. Other model layers have exactly the same configurations while the layer thickness may vary. Figure 19 zooms in to the well field located in the centre of Figure 18. The main Y-axis of the mesh is along the NW at 325°. We assume that both the northeast part and southwest part of the reservoir are symmetrical,

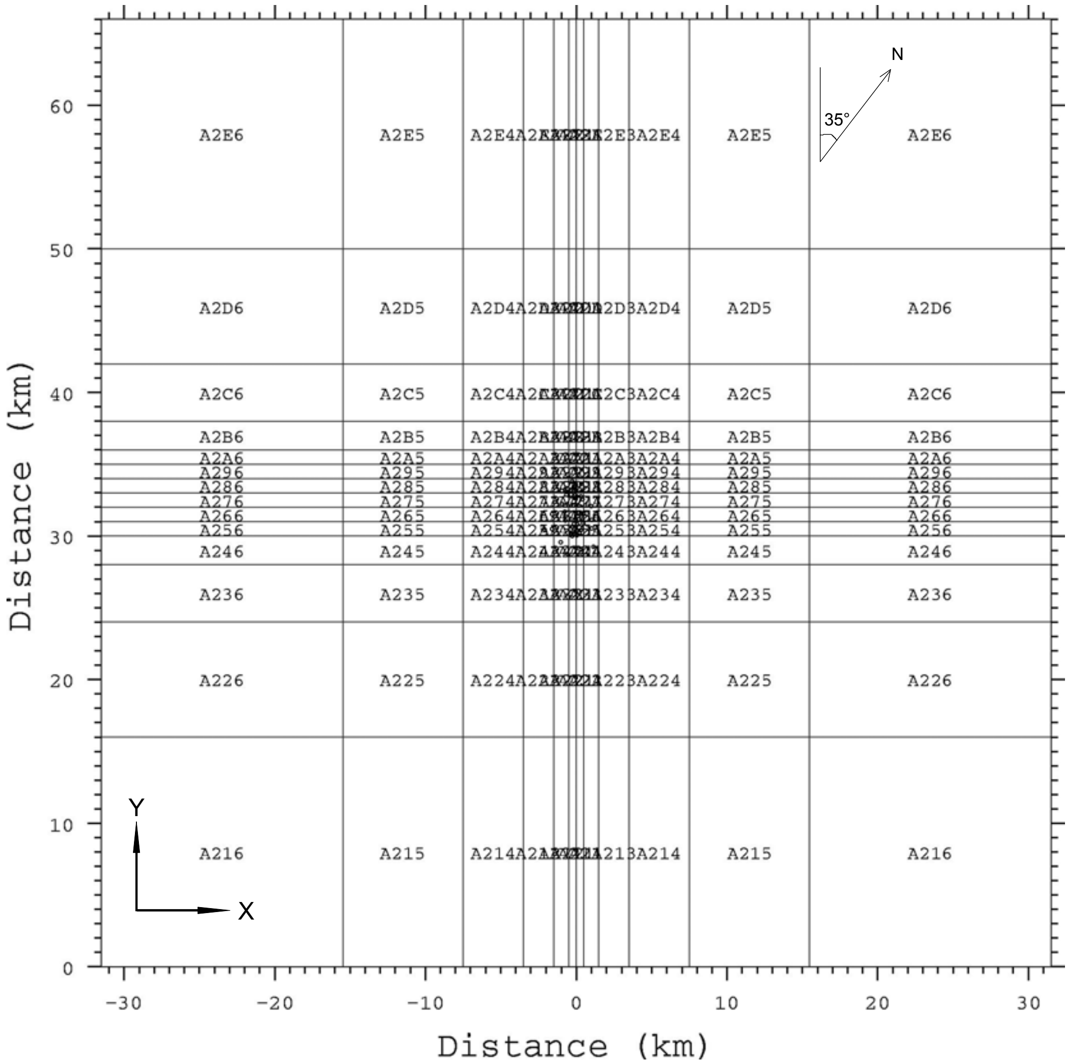

FIGURE 18: A plane view of the Yangbajing mesh, including names of each element in layer 2

meaning that only the northeast half is to be simulated and mirrored to make up for the southwest part. Along X-axis we make a mesh interval of 500, 1000, 2000, 4000, 8000 and 16000 m. The total length of the X-axis is 63 km. Along the Y-axis we make a mesh interval of 16000, 8000, 4000, 2000, 1000, 1000, 1000 m from the south to the grid centre and duplicate those distances to the north to make the mesh symmetrical around the deep wells. The total length of the Y-axis is 66 km. This way the mesh is of highest resolution near the upflow zone and inside the wellfield. The outer elements, on the other hand, are very large and represent the poorly known outer boundaries of the numerical model.

Figure 20 shows a cross-section view of the model mesh. The plot is not to scale vertically. We assume the ground surface to be at an elevation of 4300 m a.s.l., i.e. at the centre of layer 1. The vertical thickness of the model is 2.9 km. It is divided into 7 layers, which thicknesses are 200, 100, 200, 400, 500, 500 and 1000 metres, from the top down.

The plane area of the numerical model is 4158 km^2. The total volume of the model is 12058 km^3. There are 1176 elements in this model, where the volume of the smallest element is 0.05 km^3 and 256 km^3 for the largest element.

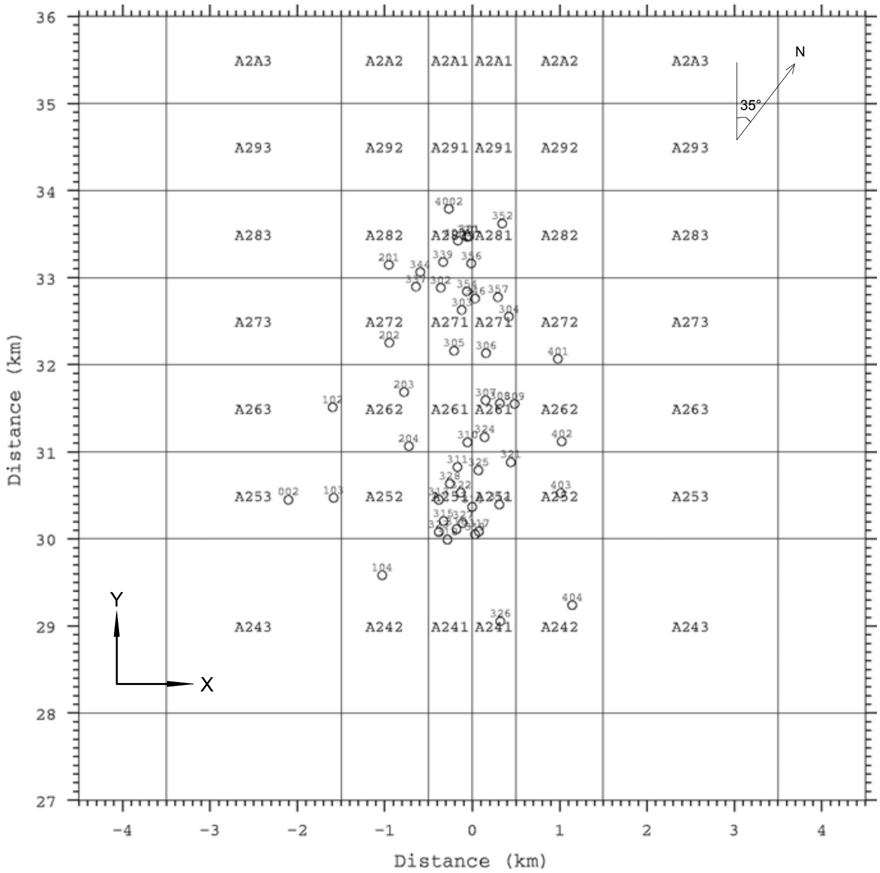

FIGURE 19: A blow-out of the well field and the numerical mesh; wells are shown by open circles

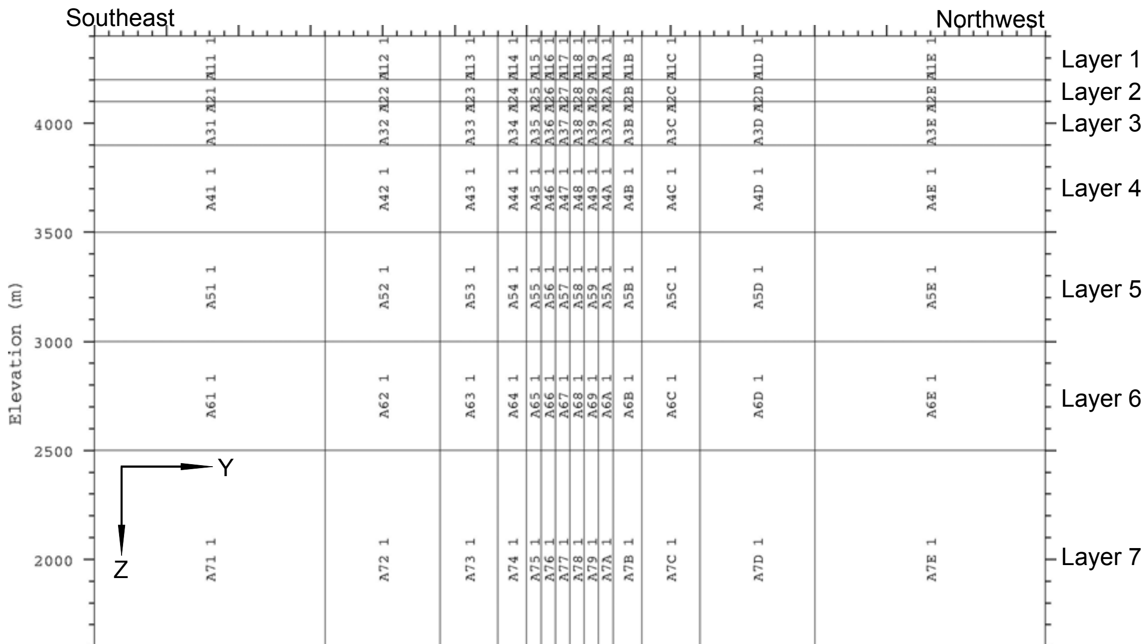

FIGURE 20: A cross-section view of the Yangbajing mesh, including names of each element

6.2 Model parameters and calibration

The goal in setting up a numerical model of a geothermal system, is to generate a mesh which correlates to the conceptual reservoir model. Also, to assign rock properties to all the elements of the model mesh and, by trial and error, simulate the field data available. In the case of Yangbajing, basically we only know the temperature of the shallow system (Figures 6, 7, 8, 9, 10 and 11) and in a deep cross-section (Figures 12, 13, and 17). Table 4 shows the rock properties chosen here to simulate these sets of temperature data.

TABLE 4: Rock parameters used in the Yangbajing numerical model

No.	Rock type	Density (kg/m^3)	Porosity (%)	PER(1) (m^2)	PER(2) (m^2)	PER(3) (m^2)	Thermal conductivity (W/m°C)	Heat capacity (J/kg°C)
1	Rock	2650	10	1.0E-15	1.0E-15	1.0E-16	2.5	1000
2	Basement	2650	10	1.0E-16	1.0E-16	1.0E-16	2.5	1.00E-15
3	Upflow	2650	10	1.0E-15	1.0E-15	25.0E-15	2.5	1000
4	Reservoir	2650	10	5.0E-15	250.0E-15	20.0E-15	2.5	1000
5	Caprock	2650	10	1.0E-18	1.0E-18	1.0E-18	2.5	1000
6	Boundary	2650	10	1.0E-15	1.0E-15	1.0E-16	2.5	1000

PER(I), I=1,2,3 - permeabilities along X, Y and Z axes

In the simulation study we define six different rock types (Table 4, Figure 21). Type 1 is the main rock of the Yangbajing well field. This rock type has a low permeability (1 mD). All blocks of layer 7 are defined as basement rock (type 2) also with low permeability. Its thermodynamic state remains constant

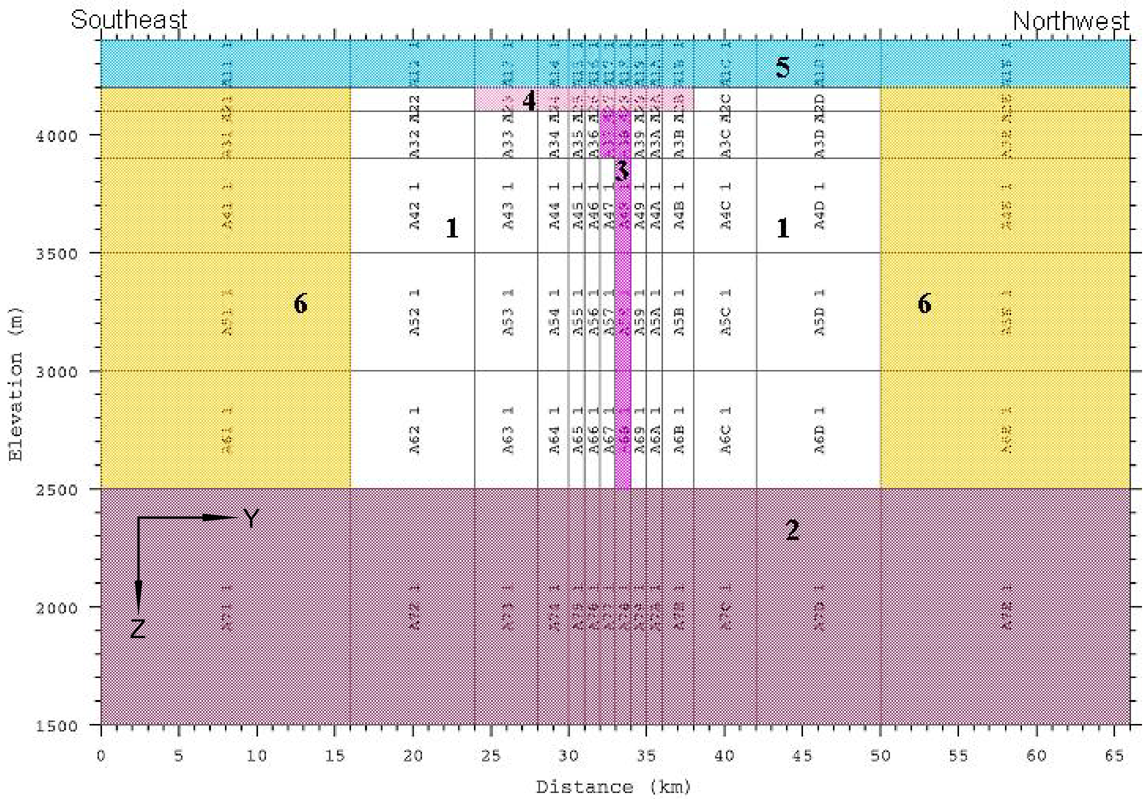

FIGURE 21: Rock distribution in the cross-section in Figure 19;
bold numbers refer to the rocks shown in Table 4

at all times (200°C and 216 bars). Rock type 3 is defined as fractures belonging to the hot upflow zone (elements A681, A581, A481, A381 and A371). Rock type 4 is defined as the horizontal shallow reservoir, which includes model elements A231, A241, A251, A261, A271, A281, A291, A2A1 and A2B1. All elements of layer 1 are defined as cap-rock (type 5) with very low permeability and also assumed to be in steady-state condition (5°C and 0.6 bar). Finally all the other outer boundary elements of layers 2-6 are defined as type 6. The rock as type 6 is the same as type 1. All elements of type 6 are assumed to remain at steady-state condition, which is defined as a linear temperature and pressure gradients between the steady-state layers 1 and 7 (8.5°C/100m and 9.37 bar/100 m).

A mass source is located in element A681 where a constant inflow of 25.5 kg/s of water at 1500 kJ/kg (325°C) takes place. We also assume that elements A231, A232, A233, A243 and A253 serve as "safety valves", i.e. if the element pressure exceeds a certain reference pressure, an outflow will take place from the element to the surface. In nature, these correspond to the surface geothermal manifestations.

6.3 Matching the field data

Figure 22 shows in a cross-section the calculated model temperature. It shows that the upflow of thermal water occurs along fracture rock type 3 and turns laterally into the shallow reservoir via rock type 4. Figure 23 shows the computed pressure in that same cross-section. It also shows a pressure anomaly associated with the model upflow zone.

Figure 24 shows in a plane view the calculated model temperature in shallow reservoir layer 2. The high-temperature centre concentrates in the Northern field. The highest model temperature exceeds 230°C, while the highest computed well temperatures are between 200 and 220°C, to be compared with the measured 170°C maximum. The shape of temperature isolines are, however, similar to the measured temperatures (Figures 9 and 10). Figure 25 shows the calculated pressure data in the same shallow reservoir layer 2. There is a computed high-pressure centre in the shallow reservoir of the Northern part,

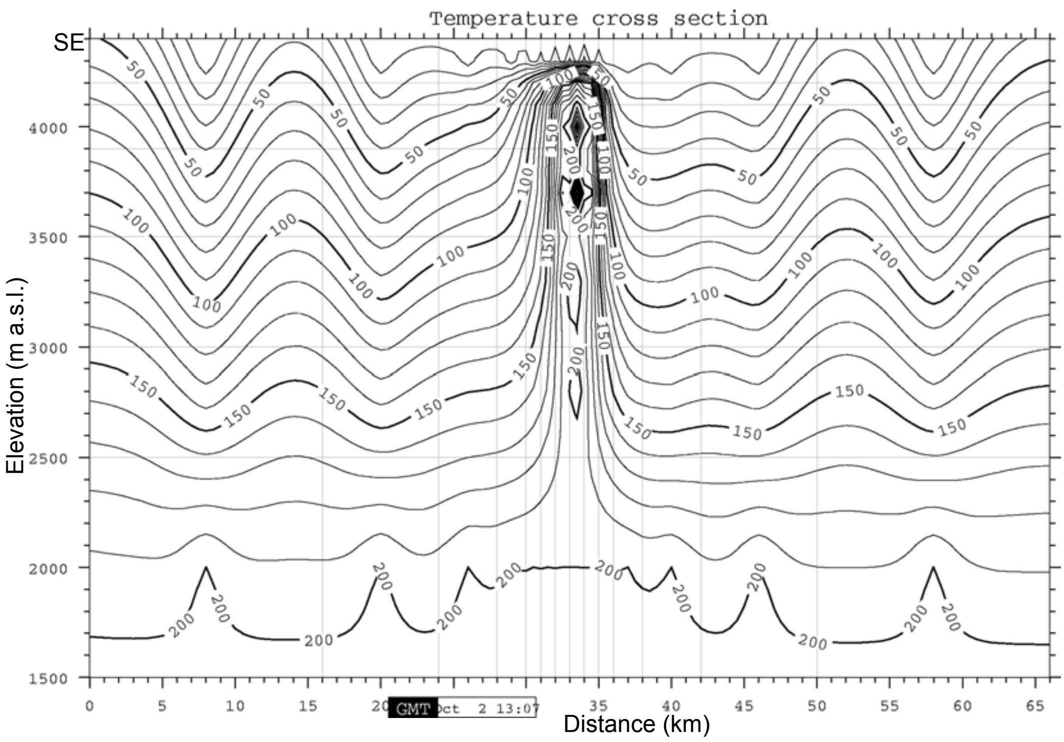

FIGURE 22: Computed model temperature (°C) in a cross-section

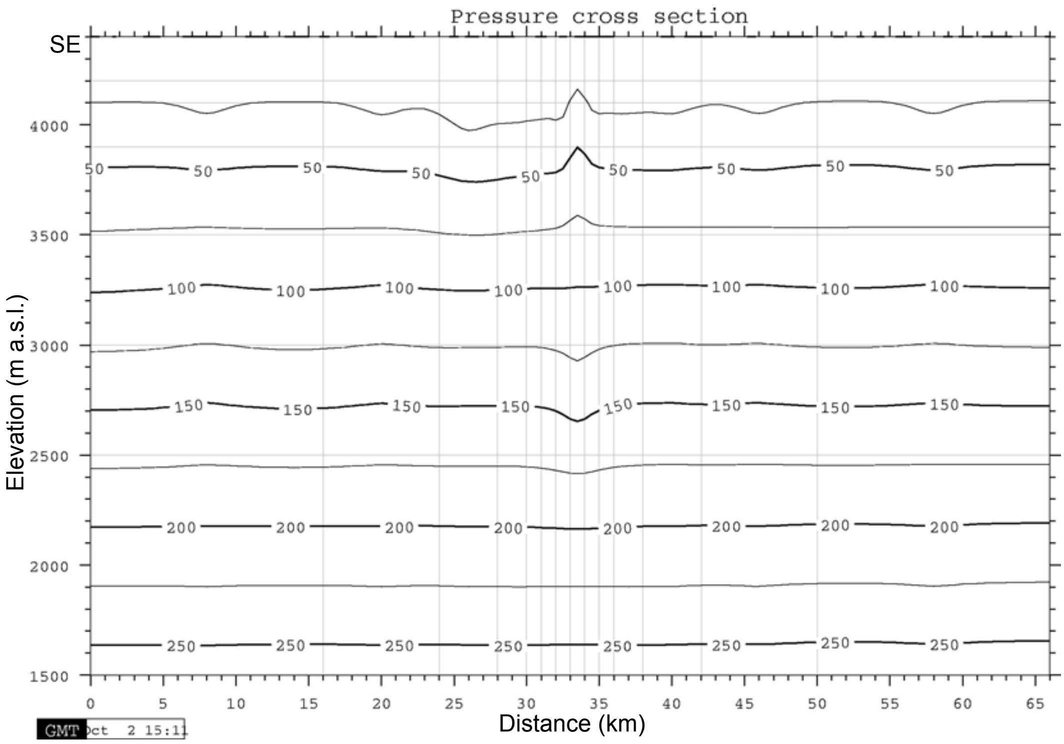

FIGURE 23: Computed model pressure (bar-a) in a cross-section

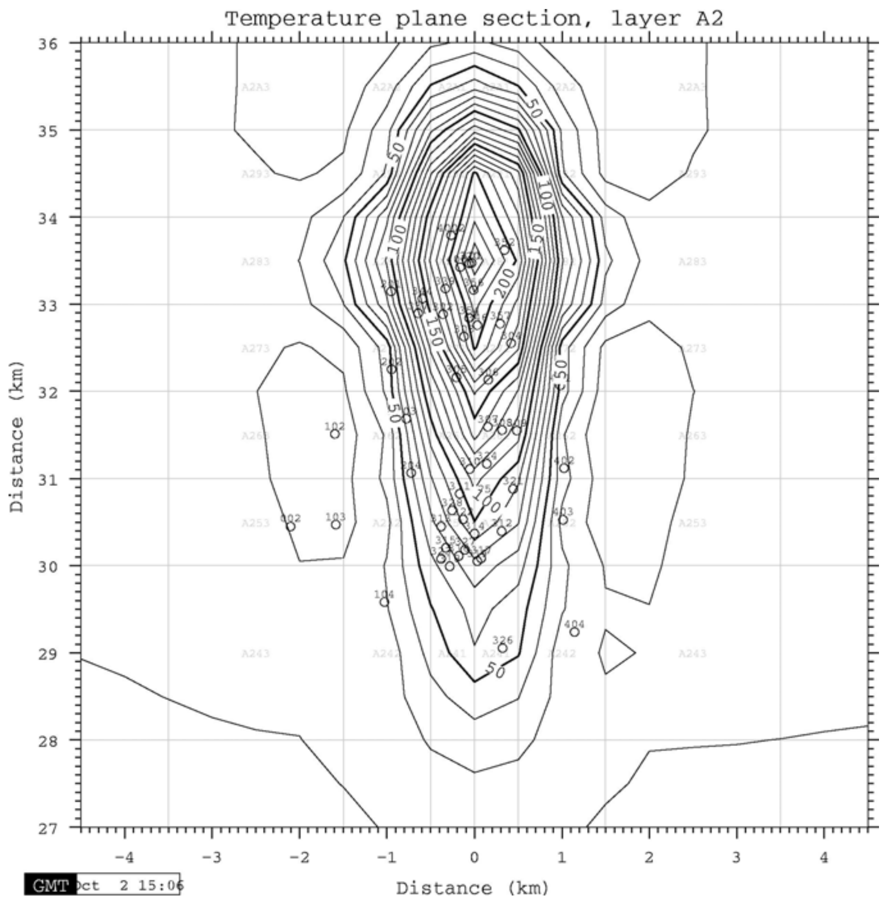

FIGURE 24: Computed temperature in the shallow reservoir (°C)

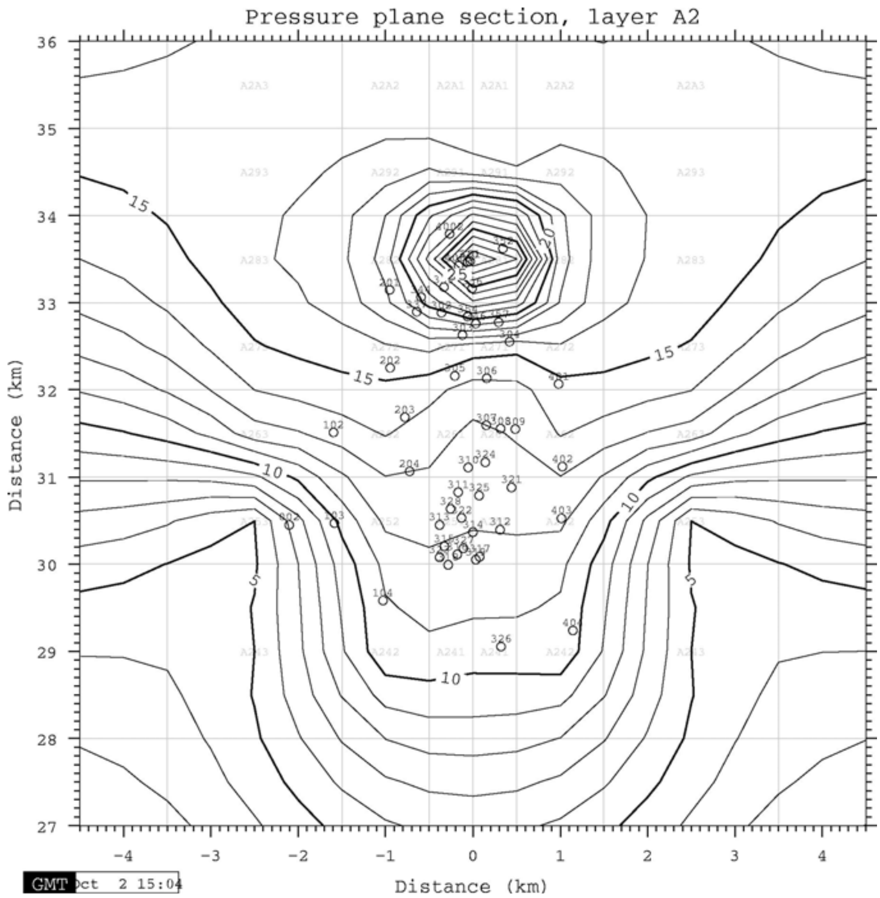

FIGURE 25: Computed pressure in the shallow reservoir (bar-a)

which forces the thermal water to flow from the Northern part to the south. Unfortunately, this study was unable to come up with field data that may confirm or reject this computed, lateral pressure gradient of about 20 bars.

We selected 12 model elements for comparing the computed and the actual well temperatures (Figures 26 and 27). The well locations are shown in Figure 19. Some of the temperature profiles show a good match, while others are fair to poor. There are some reasons for this. Firstly, the model grid is very coarse, making detailed matches very difficult. Secondly, some of the temperature data may be heavily disturbed by drilling, flow, etc. Therefore, it may not present the true reservoir temperature.

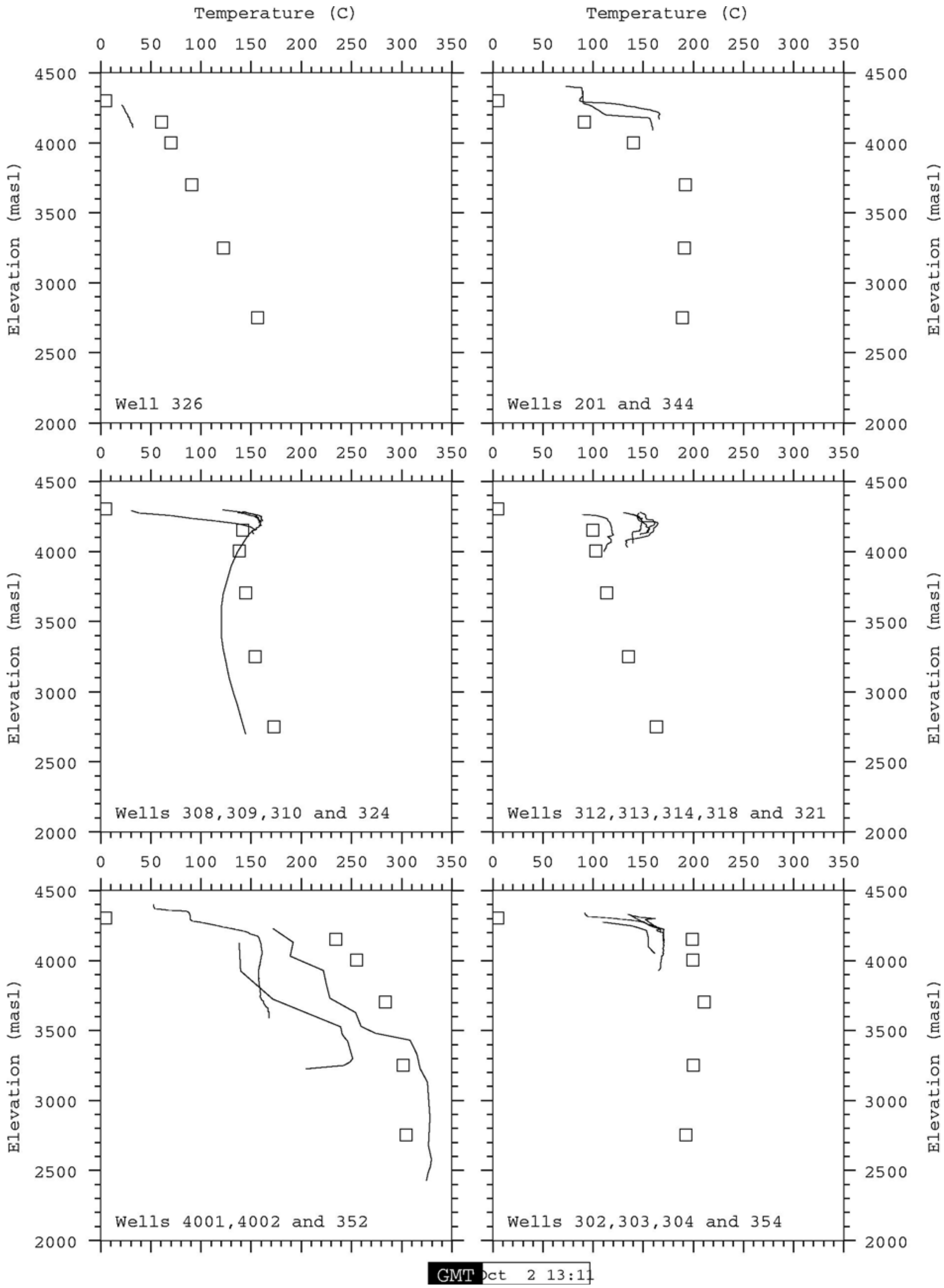

FIGURE 26: Comparison between observed and calculated temperature profiles in selected wells; solid lines present well temperatures and open boxes the computed model temperatures

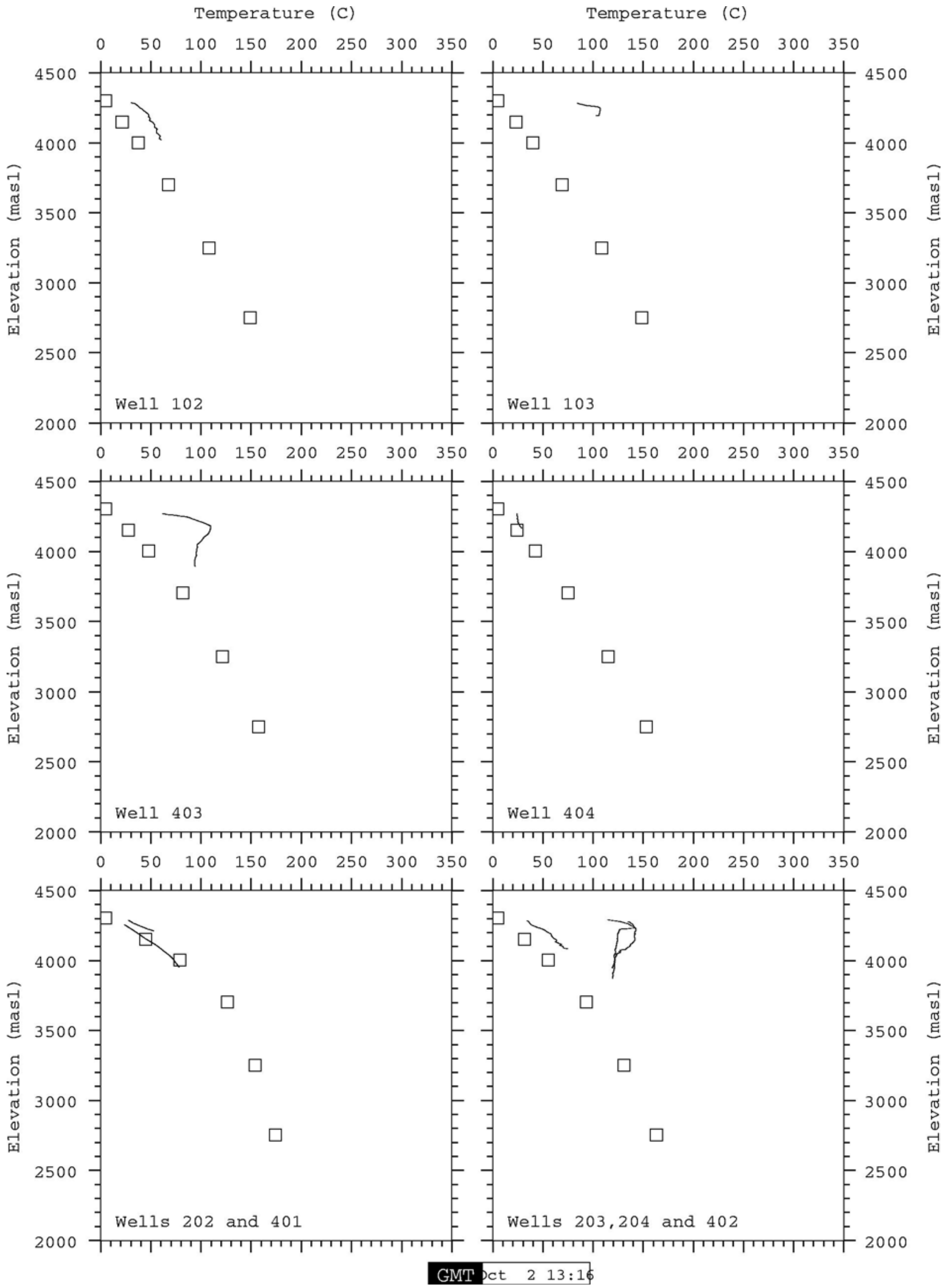

FIGURE 27: Comparison between observed and calculated temperature profiles in selected wells

7. CONCLUSIONS

The main conclusions of this report on the Yangbajing geothermal system are as follows:

- Field data on the Yangbajing reservoir have been collected from many sources, digitized and scanned to make up a comprehensive database.

- To date, at least 54 wells have been drilled into the resource, ranging in depths between 75 and 2000 m depth. Most of them are shallow and had initial electrical output in the range of 0.5-1.5 MWe. However, by drilling deep into the upflow zone of the system, one well is now able to generate more than 10 MWe.

- The study confirmed earlier work on the Yangbajing system. The system is divided into a shallow horizontal reservoir of 150-170°C temperature at 180-280 m depth below surface; and a deep reservoir (1000-2000 m) where temperatures are between 250 and 320°C.

- The hot upflow zone resides in the north and is possibly associated with a hanging wall of a large fault. Rocks are here of volcanic and intrusive origin.

- The flow direction changes from vertical to horizontal when entering the sedimentary shallow reservoir. The geothermal fluid then flows towards the south-southeast. Hot springs and thermal lakes finally discharge the geothermal fluid to surface.

- The shallow reservoir is assumed to have an area extent of 15 km^2 while the deep one covers less than 4 km^2.

- The geothermal fluid may originate as glacial melt at high elevations, but when heated at depth it becomes saline (2.8 g/l chloride). Mixing with fresh water occurs in the shallow system, resulting in a salinity of 1.5 g/l.

- Considerable land subsidence has followed production and pressure decline in the shallow and sedimentary reservoir. Subsequently, some of the wells to the south now show reservoir cooling due to colder boundary recharge while wells to the north have become slightly hotter as a result of increased recharge from the deep system.

- A 3-D numerical TOUGH2-EOS1 model was developed to simulate the estimated initial temperature distribution. It is composed of 1176 rectangular elements in 7 horizontal layers and is made of only 6 rock types.

- The model was able to simulate reasonably some of the measured well temperatures in Yangbajing. In the present state, the large field permeability is estimated in the range of 0.1-5 mD. Permeability in the vertical upflow zone is near 20 mD and in the shallow reservoir a 250 mD permeability came up as the best model. The numerical model is heated from below by a constant 25 kg/s source of 1500 kJ/kg enthalpy (330°C).

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