The United Nations University

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Geothermal Training in Iceland 1998

Reports of the United Nations University Geothermal Training Programme, 1998

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Geothermal Training Programme in 1998

Edited by
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INTRODUCTION

In 1998, we celebrated the 20th anniversary of the UNU Geothermal Training Programme. There were 16 UNU Fellows from 10 countries (China, El Salvador, Ethiopia, Iran, Kenya, Pakistan, Poland, Romania, Tunisia, and Turkey) who completed the 20th annual course, four ladies and twelve gentlemen. They were all on Fellowships from the Icelandic Government and the UNU. We had also an excellent geochemist from Costa Rica on a four month Fellowship from the International Atomic Energy Agency. The reports of these seventeen Fellows are presented in this year book. Since the establishment of the programme in 1979, 213 scientists and engineers from 35 countries have completed the six months courses. They have come from Asia (45%), Africa (26%), Central America (15%) and Central and Eastern Europe (14%). There have been 27 ladies, or 13%. In addition, over 70 people have received shorter training (2 weeks to 4 months). The teachers were mostly the same in 1998 as in the last few years, and the permanent staff was the same (Ingvar B. Fridleifsson (director), Lúdvík S. Georgsson (deputy-director), and Gudrún Bjarnadóttir (administrative assistant)). During the year, site visits were made to evaluate geothermal training needs and to select new UNU Fellows in El Salvador, Guatemala, Philippines and Poland.

The highlight of the year was the 20th Anniversary Geothermal Workshop held in Reykjavík on 13-14th October 1998. The workshop was attended by some 120 participants including 38 current and former UNU Fellows. There were 16 UNU Fellows who were completing their training, 15 UNU Fellows from the years 1979-1994, 6 UNU Fellows attending the newly established UNU Fisheries Training Programme in Reykjavik, and last but not least Dr. Abraham Besrat, Vice-Rector of the UNU, who first came in contact with the UNU as a UNU Fellow from Ethiopia.

The workshop was opened by addresses from Mr. Halldór Ásgrímsson, Foreign Minister of Iceland, and Professor Hans van Ginkel, Rector of the UNU. Mr. Ásgrímsson expressed his deep appreciation for the exemplary cooperation that has developed over the past twenty years between the UNU and the Government of Iceland that has made it possible for young scientists and engineers from developing countries to receive high level training in the development and utilization of an energy source that is not only sustainable but friendly to the environment. He was pleased that his country was able to make a significant contribution in the high-level manpower development particularly in developing countries. The Foreign Minister lauded the hard work and dedicated effort of the staff in making the UNU Geothermal Training Programme highly successful. He said that a significant portion of Iceland's aid for international development will continue to be channelled for supporting the development of high-level manpower in the UNU Geothermal Training Programme as well as in the UNU Fisheries Training Programme which was inaugurated in August 1998 at the Marine Research Institute as another collaborative activity between the Government of Iceland and the UNU, and possibly other areas.

In his keynote address the Rector said that this year also marks the 20th anniversary for the UNU to have Orkustofnun as one of its associated institutions and expressed his deep appreciation for the long history of cooperation that has existed between Orkustofnun and the UNU in the development of high-level experts in geothermal exploration and development. He expressed his sincere appreciation to the people and Government of Iceland for the steadfast and generous support for the activities of the UNU. He described the relationship as an exemplary institutional linkage within the UNU family, and said the UNU Geothermal Training Programme was an excellent model for the UNU to follow in its other programmes. In his address, the Rector expressed his continuing commitment to strengthen the academic capacity of the UNU Centre with the intention of working more closely and effectively with the existing UNU associated and cooperating institutions like Orkustofnun as well as new partners. He emphasized the need for the UNU to utilize the networking principle more effectively by forging strategic alliances that will help the UNU to focus its work with key partners and by associating with a larger number of institutions. The Rector made a commitment to provide support to a limited number of former UNU Fellows for participating in the World Geothermal Congress that will be held in Japan in 2000.

A total of 29 papers were presented at the two-day workshop by former UNU Fellows who were invited for the event, many of the 1998 UNU Fellows and selected experts from Iceland. The papers of the invited speakers will be published separately by the UNU Geothermal Training Programme. Ms. Agnes

Reyes (Philippines /New Zealand), who was one of the first two UNU Fellows in 1979 when the programme started, and the 1998 UNU Visiting Lecturer, presented a keynote paper on the development of petrological techniques in the exploration and exploitation of Philippine geothermal systems. At the end of the workshop, she spoke on behalf of the current and former UNU Fellows thanking all of the staff of Orkustofnun and the other Icelandic experts involved for the excellent training in Iceland and the follow up support they continue to provide to the former advisees. This has resulted in forming a strong professional bond between the former Fellows and the Icelandic experts as well as between UNU Fellows in the various countries. On behalf of the recipient countries, Mr. Wang Ronghua, ambassador of the Peoples Republic of China to Iceland, thanked the UNU Geothermal Training Programme for the very significant contribution the programme has made to the modernisation of geothermal research and development in his country as well as in other developing countries. Many of the leading scientists and engineers in geothermal work in China have received their specialized training in Iceland.

Dr. Abraham Besrat, UNU Vice Rector, made a presentation on the overall UNU Training and Fellowship Programme. In his remarks at the closing session of the workshop he reiterated the appreciation of the UNU for the generous support the Government of Iceland continues to provide to the UNU. He said that the support provided to the Geothermal and Fisheries Training Programmes may soon reach the level of one million US dollars per year which may represent the highest per capita contribution to the UN system by any industrialized country. He welcomed the intention of the former UNU Fellows trained in Iceland to establish an alumni association.

We hope that all of you who receive this volume will think of whether anybody in your institution/country might benfit from sharing it with you. We want to remind the readers that the reports are written as a part of an academic exercise and in most cases under a considerable time pressure. The reports have been written under close guidance of the supervisors. We are grateful for the dedication of the Fellows and the teachers in their work at the UNU Geothermal Training Programme.

We regularly send up-dates of the e-mail address directory (presently over 80 addresses) to all UNU Fellows. Those, who have not done so earlier, are requested to send their e-mail address to my address (ibf@os.is). Also you should visit our recent home page at www.os.is/unugtp/

With warmest regards from Iceland, Ingvar B. Fridleifsson, director,

Information about the UNU Geothermal Training Programme

The Geothermal Training Programme of the United Nations University has operated at Orkustofnun (the National Energy Authority) in Iceland since 1979 with six months annual courses for professionals who mostly come from the developing countries. Candidates must have a minimum of one year practical experience in geothermal work in their home countries prior to the training. Specialised training is given in geological exploration, borehole geology, geophysical exploration, borehole geophysics, reservoir engineering, environmental studies, chemistry of thermal fluids, geothermal utilization, and drilling technology. Each trainee attends only one specialized course. The training is conducted in English.

The trademark of the training is to give university graduates engaged in geothermal work very intensive on-the-job training in their chosen fields of specialization. The trainees work side by side with geothermal professionals in Iceland, mostly staff members of Orkustofnun, an agency actively working on most aspects of geothermal exploration and development. The training is tailor-made for the individual and the needs of his institution/country. The aim is to assist developing countries with significant geothermal potential to build up groups of specialists that cover most aspects of geothermal exploration and development. Priority is given to candidates from institutions where geothermal work is already under way. All candidates are selected by private interviews and receive scholarships (covering tuition, per diem and international travel) financed by the Government of Iceland and the UNU. Upon completion of their training the participants receive a UNU Certificate. During 1979-1998, 213 scientists and engineers from 35 countries have completed the 6 month course. Further description can be found at our new internet home page: www.os.is/unugtp/ .

TABLE OF CONTENTS

The United Nations University

GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
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Number 1

A CONCEPTUAL RESERVOIR MODEL AND PRODUCTION CAPACITY ESTIMATE FOR THE TENDAHO GEOTHERMAL FIELD, ETHIOPIA

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ABSTRACT

In this report the 6 wells drilled in the Tendaho geothermal field are briefly described. Formation temperatures and initial pressures for each well are estimated and a conceptual reservoir model presented. The Tendaho reservoir is divided into a shallow sedimentary reservoir with temperatures of 220-250°C and a deep one in volcanic basalts, ranging from 220 to 270°C in temperature. Inflow comes from depth in the east and the fluid flows diagonally to the surface, causing reversed temperatures in the present wellfield. Production data analysis indicates permeability-thickness in the range of 3-10 Dm in the shallow reservoir. A wellbore simulator study shows that the present wells maintain high flowrates despite either a 5 bar reservoir drawdown or a 20°C reservoir cooling. Both volumetric reservoir assessment and TOUGH2 reservoir model indicate that the present wellfield can sustain a 70 kg/s production rate for 20 years. Installing a small 1-2 MWe back pressure pilot plant seems feasible as an intermediate goal in the research activities. This, however, requires up to 1 year of testing the flow in order to define the nature of the outer reservoir boundaries. As more production and subsurface data become available, this very pessimistic production capacity estimate should be reconsidered.

1. INTRODUCTION

Investigations for geothermal resources in Ethiopia date back to 1969, to a joint venture launched by the UNDP and the Ministry of Mines, Energy and Water Resources of Ethiopia. The reconnaissance survey identified around 20 geothermal prospect areas in the Ethiopian rift valley. The three areas chosen for detailed studies were Lakes District, Tendaho and Dalol (Figure 1). The first 8 deep geothermal exploratory wells were drilled in the Lakes District at Aluto-Langano geothermal field from 1981 to 1985. A combined binary cycle pilot power plant with a capacity of about 7.8 MWe from the 4 productive wells is under construction.

The Tendaho geothermal field is located in the northeastern part of Ethiopia, in the Afar administrative region. Out of the many geothermal prospect areas in the Ethiopian rift valley, it is the second geothermal field to be explored by drilling of deep exploratory wells.

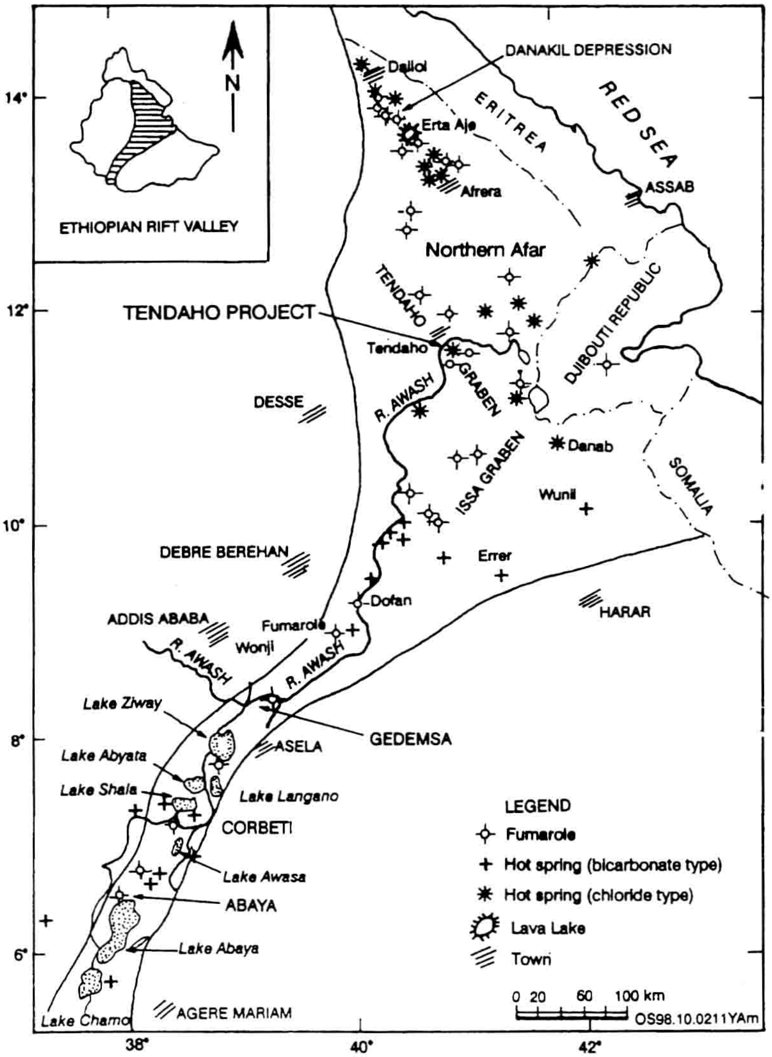

FIGURE 1: Geothermal areas in the Ethiopian rift valley

The geothermal exploration in Tendaho was carried out in three phases. During the first phase, geological, geochemical and geophysical surveys were conducted. Eight shallow temperature gradient wells were also drilled. The results of the different surveys indicated the availability of a geothermal reservoir. Drilling of three 2000 m geothermal wells was recommended.

Based on the recommendations of the first phase, drilling started in October, 1993. Three deep wells and one shallow well (1-4) had been drilled by May 1995 (Figure 2). These wells led to the discovery of a shallow reservoir in the vicinity of wells TD2 and TD4. Exploiting the shallow reservoir by drilling two additional shallow wells around well TD4 (wells TD5 and TD6) was recommended.

The first and second phases of geothermal exploration studies were carried out by Aquater, an Italian government company, in collaboration with the Ethiopian Institute of Geological Surveys. The drilling of 3 deep wells and one shallow well was concluded by submission of a final report (Aquater, 1996).

Phase 3 had the objective to prove the potential of the shallow reservoir and to study its characteristics. Drilling of the two shallow wells commenced on December 20, 1997 and was completed on February 20, 1998. The existence of a shallow 230-250°C liquid-dominated reservoir was confirmed in the Tendaho cotton plantation (often called Dubti). The three shallow wells TD4, TD5 and TD6 are all productive (Figure 2).

The Afar administrative region is under rapid development. The new capital city of Afar, Semera, is located within the premises of the geothermal field. The Awash river, which provides a steady supply

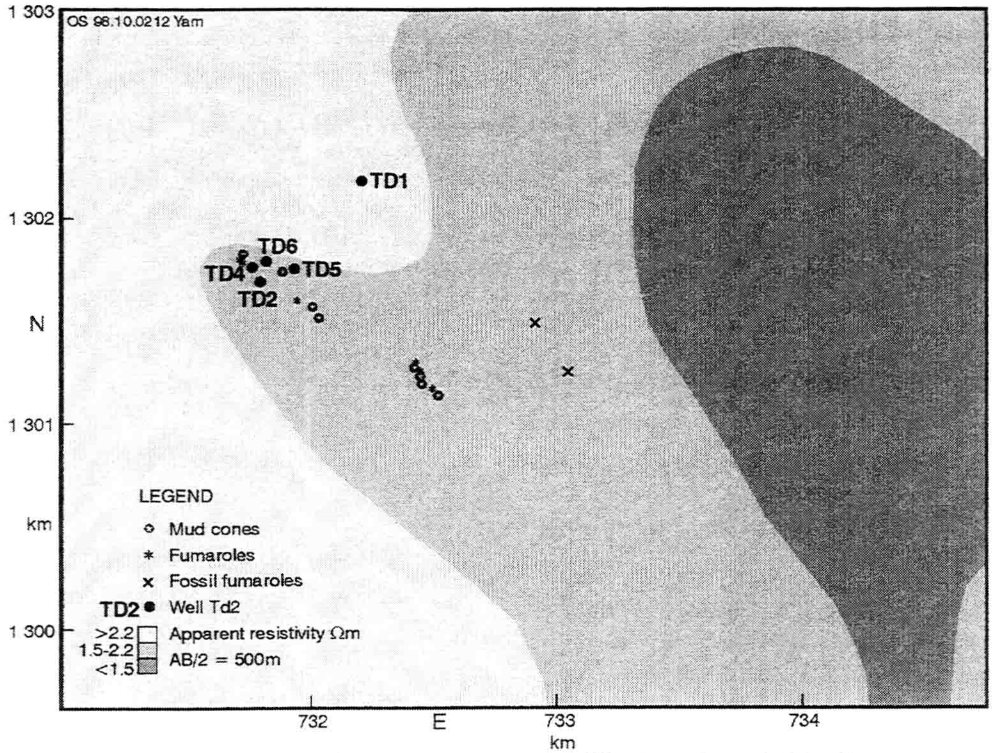

FIGURE 2: Location map of Tendaho geothermal wellfield and the resistivity distribution

of fresh water for agriculture, is close by the geothermal field. Faster growth of this area is, however, constrained by lack of electricity, both for households and irrigation. At present only diesel electricity is available. A successful operation of an electrical power plant in Tendaho may, therefore, become a key element in future living conditions in the area.

In this report the 6 wells drilled in Tendaho are briefly described. The formation temperatures and initial pressures for each well are estimated. From the formation temperature and pressure distribution, a conceptual reservoir model is constructed. Production data are analysed and future well performance for two wells predicted. Pressure transient tests from the newly drilled wells are analysed and permeability estimated. Resource evaluation for the shallow reservoir is carried out by applying the volumetric method. In order to determine the confidence intervals of the volumetric resource assessment method, the Monte Carlo statistical method is employed. Additional modelling work is done by the reservoir simulator, TOUGH2, in order to support the conclusions drawn by the volumetric method. Finally, the size and pre-feasibility study of a small pilot power plant instalment is discussed.

2. DATA SOURCES

2.1 Stratigraphy, chemistry and resistivity

Tendaho geothermal field is located in the northeastern part of Ethiopia, some 600 km from the capital city, Addis Ababa (Figure 1). It is one of the three geothermal prospect areas within the Tendaho graben, which covers an area of about 4000 km^2. Two deep and three shallow wells have been drilled in the thermally active zone of the Dubti area and one additional deep well (TD3) was drilled 7 km away from the rest of the wells. Information about the wells in the Tendaho are summarized in Table 1.

The results of drilling indicate that in the Dubti area, the upper 600-700 m are lacustrine sedimentary sequences with interlayered basalts. The lower parts are the Afar Stratoid Series, a basaltic sequence that represents the floor of the Tendaho sedimentary basin (Aquater, 1996). The water discharged from the wells is of sodium chloride type, mature from a geothermal point of view and has not mixed with surface waters. Total dissolved solids (TDS) are relatively low, with a value of 2.2 g/l for TD4 at atmospheric separator. Non-condensable gases are less than 0.2 Nl/kg. Main recharge elevation for the Tendaho geothermal system was estimated to be 3000 m a.s.l. within the upper portion of the escarpment. The northeast boarder of the Tendaho cotton plantation, where intense thermal activity is concentrated and proven to be productive, also contains low- resistivity anomaly (Oluma et al., 1996). Figure 2 shows the resistivity distribution and the location of the wells.

2.2 Downhole temperature and pressure

Most of the temperature and pressure data for wells 1-4 were collected by Aquater (1994a and b; 1995a and b) as measurements and well testing were part of the drilling contract. The remaining data were collected by the Ethiopian Institute of Geological Surveys. A total of 131 temperature and pressure surveys are considered in this report. Downhole temperature and pressure surveys were carried out by using Amerada and Kuster mechanical gauges. As the elevation difference between the wells is less than 2 m, downhole profiles are plotted against depth from ground level. The location of the wells and the elevation data are based on recent geodetic survey results (Belete, 1998).

TABLE 1: An overview of the Tendaho geothermal wells

Well No.	TD1	TD2	TD3	TD4	TD5	TD6
Drilling date						
From	29/10/93	13/03/94	07/09/94	27/04/95	20/12/97	01/02/98
To	27/02/94	10/05/94	19/10/94	09/05/95	14/01/98	20/02/98
Location (UTM)						
East (m)	73237708	731412	728652	731363	731558	731670
North (m)	1303746	1302823	1309451	1302941	130290	1302919
Elevation (m a.s.l)	365.9	365.7	366.8	365.2	366.3	366
Well design						
Casing depth (m): 20"	130.5	111	62	24	47.6	40
13 3/8"	575	607	404.5	109	136	123
9 5/8"	850	854.5	830	210	220	217
7" liner	800-1500	809-1807	681-1362	181-463	202-508	209-504
Measured depth (m)	2196/1550*	1881	1989	466	516	505
Vertical depth (m)	2196/1550*		1989	466	516	505
Kick-off point (m)		885				
Inclination (°)		17				
Direction		N50E azimuth				
Status of well	Non-productive	Productive	Non-productive	Productive	Productive	Productive

* Current depth (re-drilled depth after well collapse)

3. INITIAL WELL TEMPERATURES AND PRESSURES

3.1 General information

Temperature is one of the most important parameters needed for geothermal reservoir analysis. Information obtained from temperature logs can be useful for heat flow estimation, location of aquifers, temperature distribution in geothermal reservoirs, reservoir assessment and efficient resource exploitation management. The initial reservoir pressure is also of importance. It delineates possible upflow zones of the reservoir as a pressure high or low. It also provides an important reference for analysing production data, including completion tests for estimating reservoir permeability. Repeated pressure logs during warm-up may also show the depth of the major feed zone of the respective well (pivot point analysis).

The cross-correlation of downhole pressure and temperature, with respect to boiling, is necessary in natural state analysis. Geothermal reservoirs often are characterised by vertical cross-flow of water and steam (heat pipe). In these depth intervals, pressure and temperature follow the so-called boiling point for depth curve (BPD). In the following analysis of downhole data, the BPD is used repeatedly for estimating the phase conditions of the Tendaho reservoir.

Temperatures recorded during drilling operations are generally lower than true formation temperature. These low temperatures result because of cooling by circulating drilling fluid. As soon as circulation stops, the temperature around the wellbore begins to increase. Complete temperature recovery in a new well may take anywhere from a few hours to a few months. A long wait for temperature recovery could cause a sizeable increase in drilling costs. Therefore, predictions of formation temperatures have to be done using other methods. The methods are based on temperature logs taken during drilling stops, or collection of such logs, forming a temperature recovery curve spanning several hours to months.

The formation temperature estimation for the Tendaho geothermal wells is done by applying one of the ICEBOX software packages (Arason and Björnsson, 1994; Helgason, 1993). The program BERGHITI used here, offers two methods of calculation.

The Albright method was developed for direct determination of bottomhole formation temperatures during economically acceptable interruptions in drilling operation, 12 to 24 hours, depending on depth and rock type. This method assumes an arbitrary time interval, much shorter than the total recovery time, and that the rate of temperature relaxation depends only on the difference between the borehole temperature and the formation temperature.

The Horner plot is a simple analytical technique for analysing maximum bottomhole temperatures to determine the formation temperature. The basic criteria for the technique is a straight line relationship between the bottomhole temperatures and $\ln(\tau)$:

$$\tau = (\Delta t + t_o)/\Delta t \tag{1}$$

where Δt is the time passed since circulation stopped and t_o is the circulation time.

Using this and the fact the system must stabilize after infinite time, the bottomhole temperature as a function of $\ln(\tau)$ is then plotted. By drawing a straight line through the data and by extrapolating it to $\ln(\tau)=0$, the formation temperature can be estimated.

The following text describes briefly how the initial pressures and temperatures were estimated for the 6 Tendaho wells. Table 2 shows the numerical values of these 12 profiles.

TABLE 2: Formation temperatures and initial pressures in Tendaho wells

Well TD1			Well TD2			Well TD3			Wells TD4, 5, 6		
D (m)	**P (bars)**	**T (°C)**	**D (m)**	**P (bars)**	**T (°C)**	**D (m)**	**P (bars)**	**T (°C)**	**D (m)**	**P (bars)**	**T (°C)**
0	5.3	29	0	5.4	100	30	0.5	58.4	0	0	100
200	24.1	147.6	50	9.9	155.8	40	1.5	64.2	50	4.6	155.8
250	28.6	162.3	100	14.3	180.4	50	2.4	74.2	100	9	180.4
300	33	180.8	150	18.6	197.7	60	3.4	83.8	150	13.3	197.7
350	37.3	197.4	200	22.8	208.4	65	3.8	85.2	200	17.5	208.4
400	41.5	211.4	250	26.9	218.7	70	4.3	81.4	250	21.7	218.7
450	45.6	223.7	300	31	227.7	80	5.3	79.3	300	25.8	227.7
500	49.7	233.8	350	35.1	235.6	100	7.2	74	350	29.8	235.6
550	53.7	243.2	400	39.1	242.6	120	9.1	72	400	33.8	242.6
600	57.6	250.2	440	42.2	245	160	12.9	70	450	37.8	248.9
650	61.5	253.9	450	43	245	250	21.5	94.6	500	41.7	254.7
700	65.4	258.1	500	47	243	300	26.2	112.2			
850	76.9	267.8	600	55.1	226.8	350	30.8	130.4			
950	84.5	274	700	63.4	220.7	400	35.3	145			
1000	88.2	274.5	800	71.7	211.6	500	44.3	161.3			
1050	92	273.7	900	80.1	212	600	53.2	167			
1100	95.7	274.5	950	84.3	212.8	700	62	170			
1150	99.51	273.9	1000	88.5	213.6	800	70.9	171			
1250	107.1	271.3	1040	91.8	215.7	850	75.3	171.7			
1300	110.9	268.5	1200	105.2	220.2	900	79.7	172.1			
1350	114.7	267.5	1400	121.8	223.1	1000	88.5	173.1			
1400	118.5	266	1600	138.4	223.1	1100	97.4	174.1			
1500	126.2	267.5	1700	146.7	223	1200	106.2	176			
1600	133.8	272.6	1734	149.5	223	1300	115	177.2			
1830	151.2	279				1400	123.8	180.4			
1860	153.5	279.2				1500	132.5	184.3			
1890	155.7	279.7				1600	141.3	187.3			
1950	160.3	280.4				1700	150	190			
2160	176	282				1800	158.7	193.3			
						1900	167.3	196.3			
						1967	173.1	198.2			

3.2 Well TD1

Well TD1 was drilled to 2196 m. The formation collapsed while reaming from 944 to 973 m depth after air lifting. The present re-drilled total depth is 1550 m with a 7" liner from 800 to 1500 m depth (Table 1). Total loss of circulation occurred at 511 m which could have been a producing zone if the 9 5/8" production casing shoe was not set at 850 m. Despite the high temperature (>270°C) at depth, the well cannot sustain flow due to poor permeability.

A total of 16 downhole temperature measurements are presented in Figure 3. A formation temperature estimate through application of the Horner method is also shown. Four temperature logs were used for the estimation of the formation temperature in the depth range 950-2196 m. The temperature build-up data at 573, 842, 955 and 1980 m depths were also analysed with the Albright and Horner methods. The Albright method gave similar results to the measured static temperatures, whereas the Horner method´s estimates are lower. This could be due to the effect of circulation time.

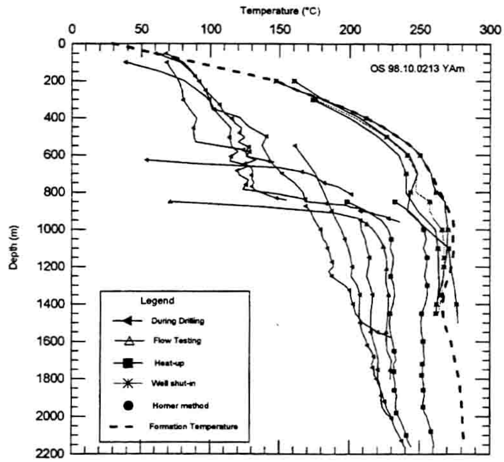

FIGURE 3: Temperature profiles in well TD1

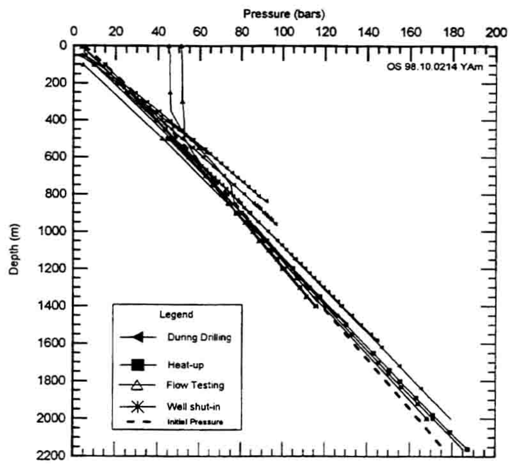

FIGURE 4: Pressure profiles in well TD1

The shape of the formation temperature suggests that the heat transfer in the upper 600 m is by conduction with an average temperature gradient of about 370°C/km. Temperature increases from the surface down to 950 m, and is constant to about 1100 m depth. From 1100 m to about 1400 m, there is temperature reversal. In the deepest part of the hole section (1700- 2200 m), the temperature gradient is positive with <20°C/km. By comparing the formation temperature profile and the boiling point with depth curve, one can conclude that the reservoir is under single phase liquid condition at all depths.

The measured pressure profiles and the initial pressure estimate are shown in Figure 4. A pivot point is observed around 900 m depth. The initial pressure is calculated from the estimated formation temperature by using the PREDYP program (Arason and Björnsson, 1994). The calculated initial pressure is almost identical to one of the measured static profiles. A feed zone is most likely at about 900 m depth with initial pressure of abut 80 bars and 270°C temperature. The shut-in wellhead pressure is stable at 5.3 bars showing that the deep reservoir is over-pressurized (well full of water).

3.3 Well TD2

Well TD2, which is located 1200 m from well TD1, was drilled to a total depth of 1811 m. It is a directional well with a kick-off point at 885 m. The reason for the drilling plan to change from vertical to directional was to cross an inferred vertical fault which was deduced from the alignment of active thermal features of the surface. The postulated vertical fault does not seem to be there. As the direction of inclination towards TD1 is not confirmed, the well is treated as a vertical well for later downhole temperature and pressure analysis.

Fourteen temperature measurements recorded at different conditions are shown in Figure 5. Five profiles were used for a formation temperature estimate applying the Horner method. The estimated temperature is near identical to a run which was measured in 1996 after 2 years of shut-in conditions. This implies that the well´s temperature is in equilibrium with the geothermal system. From the surface to about 425 m, the temperature follows the BPD curve. From 425 m to about 800 m, there is a temperature reversal. From 800 m to about 1400 m depth, temperature increases slightly and is nearly constant below 1400 m. The temperature reversal could indicate that the well is located in an outflow area of the geothermal field.

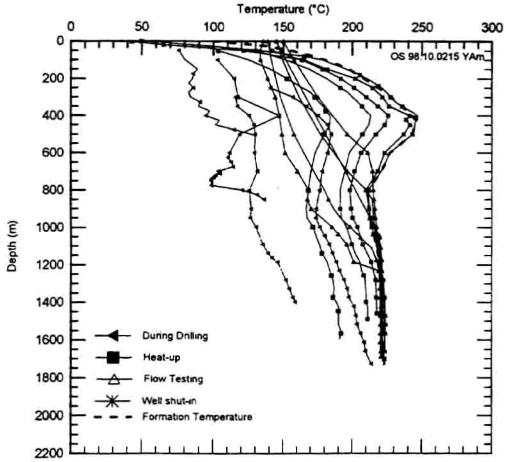

FIGURE 5: Temperature profiles in well TD2

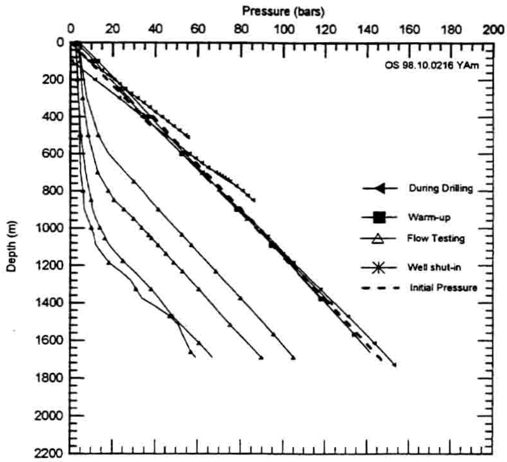

FIGURE 6: Pressure profiles in well TD2

All collected downhole pressure profiles are shown in Figure 6. A pivot point is observed at around 900 m depth, with a pressure of 80 bars. The estimated initial pressure follows the boiling depth curve from the surface to about 450 m depth, in good agreement with the measured temperature (Figure 5). Below this depth, the pressure gradient is slightly higher than that of the BPD in accordance with a shut-in wellhead pressure of 5.4 bars. This leads to the conclusion that the Tendaho reservoir can be divided into a deep and a shallow reservoir. The shallow reservoir is characterised by boiling and pressure potential in equilibrium with the surface, whereas the deep system is over-pressurised and in single phase water condition.

3.4 Well TD3

It is located at a distance of 7 km from well TD1 (Figure 2). There are no thermal activities around the well site but a high thermal gradient was measured in a nearby shallow well. The well was drilled to a total depth of 1989 m. Despite many trials to discharge the well by air lifting, the well was not able to flow because of poor permeability and low temperature.

The temperature build-up tests conducted during drilling were analysed. Estimates by the Albright method are relatively higher than the last static profile, whereas the estimates made by the Horner method are lower. The static temperature is almost the average of the estimates made by both methods (Figure 7). As it is most likely that the well temperature has stabilized in the last run, it is taken as the formation temperature. A zone of hotter fluid is clearly visible at 50 m depth from a temperature log during drilling. This indicates a geothermal outflow somewhere near the well.

The formation temperature profile suggests that the temperature gradient is about 250°C/km in the upper part of the well. Below 550 m the gradient is low (~ 20°C/km).

The initial pressure is based on the estimated formation temperature and the PREDYP program. It is presented together with pressure profiles measured during drilling and warm-up periods in Figure 8. The well has a stable water level at about 25 m depth.

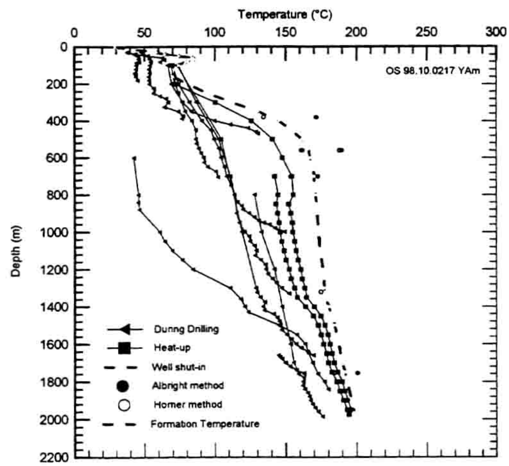

FIGURE 7: Temperature profiles in well TD3

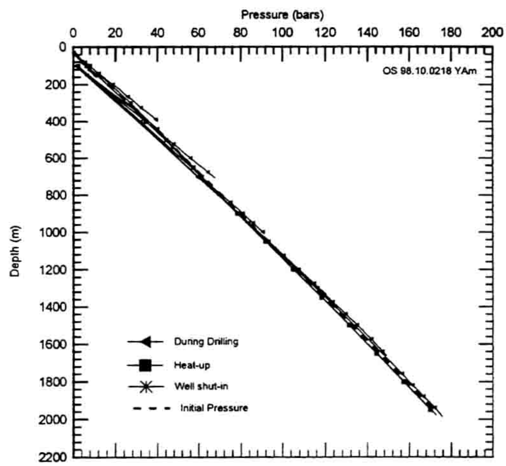

FIGURE 8: Pressure profiles in well TD3

3.5 Well TD4

It is the first shallow well (466 m) drilled in the thermally active part of the Dubti geothermal field at a distance of 120 m from the deep directional well TD2 (Figure 2 and Table 1). The well produces about 50 kg/s total of fluid at an average wellhead pressure of 13.6 bars. The corresponding enthalpy of the fluid is 1080 kJ/kg. The well produces from many feedzones, resulting in cyclic behaviour during flow.

As the drilling of well TD4 was not part of the pre-planned drilling programme, the drilling and testing time was short. As soon as the drilling was completed, the well was put to discharge. The downhole temperatures measured at different well condition are shown in Figure 9. Due to a leakage through the 10" side valve during downhole measurements, static conditions could not be attained. This is clearly visible from the similarities of the temperature profiles at shut-in and flowing conditions (Figure 9). Almost all temperature profiles follow the boiling point for depth curve below the casing. The formation temperature is, therefore, assumed to be the same as the boiling point for depth curve. Two major feed zones at around 250 m and 330 m depth are identifiable from temperature profiles taken during drilling.

Figure 10 shows pressure profiles measured during drilling, flow testing and the estimated initial pressure. The pressure pivot point is not visible, most likely due to the presence of more than one feedzone. For the major feedzone at 250 m, the initial reservoir pressure is about 22 bars. The wellhead pressure at shut-in conditions fluctuates between 20 and 22 bars, indicating a pure steam condition between the wellhead and the feedzone at 250 m. The fluctuation may be due to the cycling boiling level in the well, around 250 m depth.

3.6 Well TD5

Well TD5 is the second shallow well drilled inside the Tendaho Cotton Plantation (Dubti area), some 300 m from well TD4 (Figure 2 and Table 1). Despite indications of possible feedzones at about 300 and 500 m depths, cyclic behaviour is not observed either during discharge tests or at shut-in condition. This could mean that the production zone is from 300 m to total depth. The short term flow testing indicates that the well can produce 48 kg/s of fluid (steam and water) at 9.4 bars wellhead pressure.

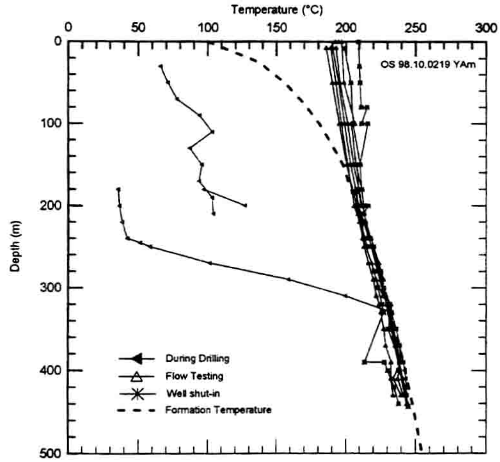

FIGURE 9: Temperature profiles in well TD4

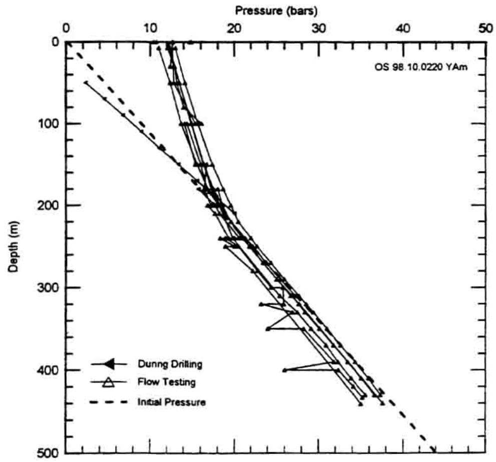

FIGURE 10: Pressure profiles in well TD4

Figure 11 shows downhole temperature profiles logged during drilling, heat-up and flow testing. The heat-up temperature profiles are almost identical. They coincide with the boiling point for depth curve from bottom hole to about 440 m depth. The formation temperature is, thus, assumed to be the same as the BPD curve. Above this depth the temperature is higher than the BPD due to the presence of gas and steam inside the casing at shut-in conditions. The measurements during flow testing through 4, 5 and 6" diameter lip pipe, respectively, show that downhole temperature decreases with increasing discharge pipe diameter. The BPD curve is crossed at 270, 140 and 100 m depth during the flow testing through 4, 5 and 6" pipes, respectively. This means that during flow, boiling will propagate into the reservoir.

The measured pressure profiles and the initial pressure profile are shown in Figure 12. The initial reservoir pressure is 34.5 bars at 400 m depth, where the pivot point is located. The wellhead pressure at shut-in condition is 21.5 bars.

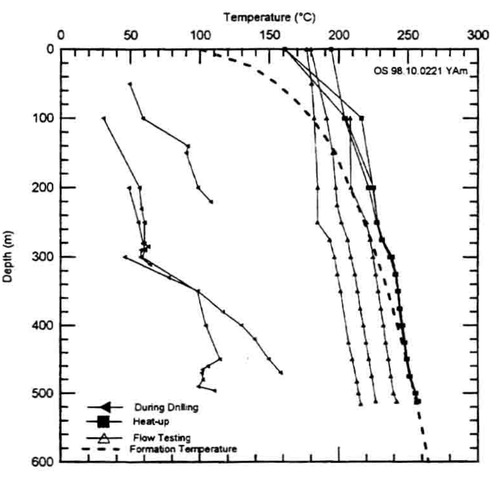

FIGURE 11: Temperature profiles in well TD5

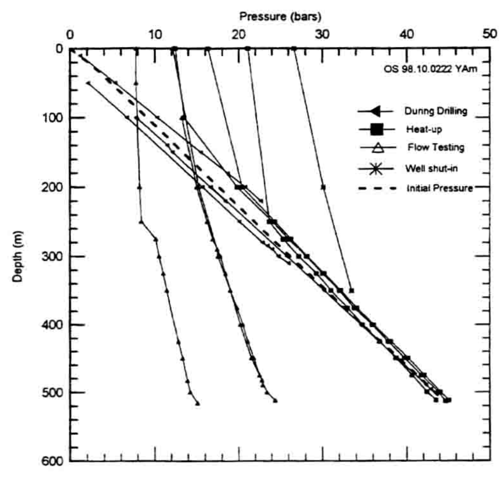

FIGURE 12: Pressure profiles in well TD5

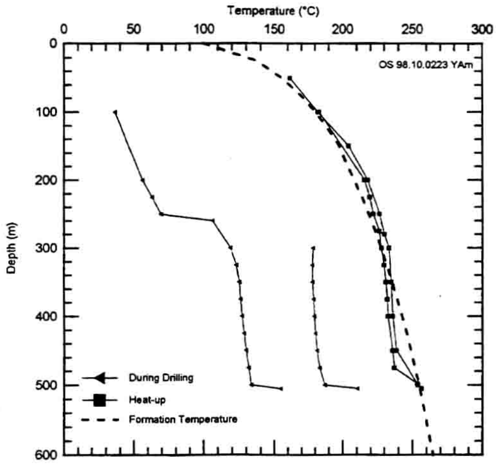

FIGURE 13: Temperature profiles in well TD6

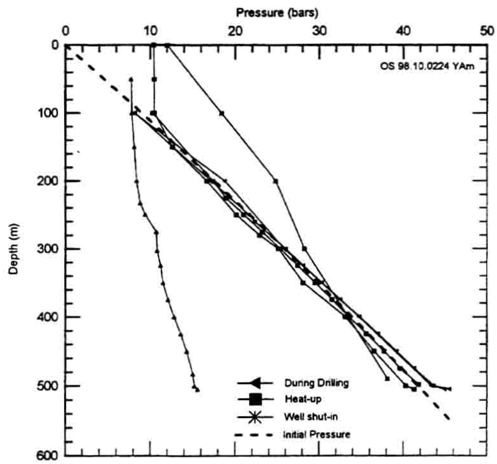

FIGURE 14: Pressure profiles in well TD6

3.7 Well TD6

It is the third shallow well drilled recently to a total depth of 505 m. The well is located between TD5 and TD4 (Figure 2 and Table 1). Due to limited drilling time, only few downhole measurements have been carried out. Furthermore, temperature and pressure measurements during the first three weeks of the heat-up period were not possible because of rig maintenance work at the wellhead.

The few available temperature profiles are shown in Figure 13. Due to the limited drilling time and the shortage of accurate low range temperature elements, temperature build-up tests were not carried out. The profiles measured during heat-up show that the boiling point for depth curve is attained. The formation temperature is, therefore, assumed to be similar to the boiling point for depth curve.

Figure 14 shows the pressure profiles of well TD6. The pivot point of the pressure profiles indicates that the major feed zone is at about 300 m. The corresponding initial reservoir pressure is then estimated to be 25.6 bars. The estimated initial pressure profile is shown in Figure 14. The shut-in wellhead pressure is about 18.5 bars.

4. A CONCEPTUAL RESERVOIR MODEL

Conceptual models are used in all stages of geothermal energy exploration and exploitation. Typically, exploration wells are located to delineate a resource, and production wells to intersect areas of high temperature and permeability. The location of these wells are, in most cases, based on a conceptual model of the reservoir. In turn, the data from new wells are then used to confirm, or more likely, improve the conceptual model (Okandan, 1988). Conceptual reservoir models also serve as an integral part of numerical reservoir models, as they provide the basis for model geometry, boundaries, recharge sites, etc.

The formulation of a conceptual model for the Tendaho geothermal field is based on the available temperature and pressure distributions, which shall be improved in the future by the drilling of new wells and longer production history.

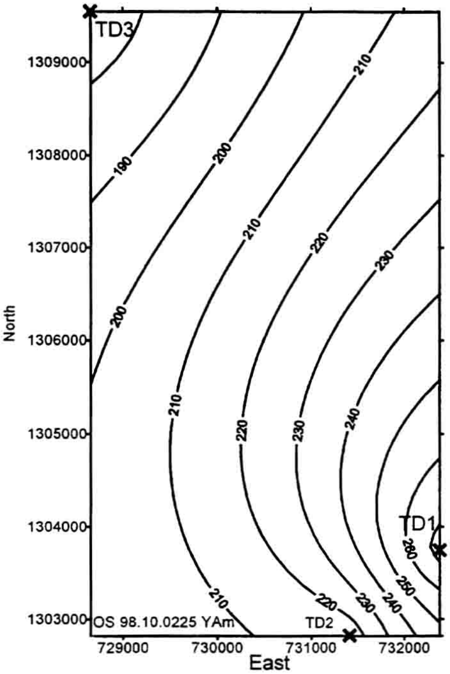

FIGURE 15: Temperature contours at 1000 m depth

Figure 15 shows a temperature contour map at 1000 m depth. The data in the figure are taken from the formation temperature profiles estimated in Chapter 3. A hot fluid recharge from east to west in the present wellfield is suggested. A temperature contour map at 450 m depth is shown in Figure 16. The low temperature and poor permeability well TD3, which is located at a distance of about 7 km, is not included in this map. The highest temperature at this depth is around the shallow wells TD4, TD5 and TD6.

Figure 17 shows a NE-SW temperature cross-section through wells TD1, TD5, TD6, TD2 and TD4. The distance between the wells shown is not exact but approximation is made for clear presentation. The higher temperature at shallow depths around well TD2 suggests that the high temperature fluid flows from depth around TD1 and then laterally to a shallower level towards TD2. The temperature reversal at TD2 is also noticeable.

Figure 17 also serves as a conceptual model for the Tendaho geothermal field. A hot fluid recharge at a temperature of about 270°C flows from the east towards well TD1. This is also suggested by the location of the low-resistivity anomaly (Figure 2). Around TD1 the recharge rises to about 1100 m and then flows towards TD4. Two reservoir domains are suggested for the Tendaho area. A shallow reservoir BPD may have a reservoir thickness of about 300 m and a temperature of 230-250°C. Due to the close spacing and the limited number of the shallow wells, the areal extent of the reservoir is unknown. From the temperature cross-section, one may assume that the geothermal reservoir lies at relatively greater depth east of TD5. In the vicinity of wells TD4 and TD2, feed zones are at a shallower level compared to that of TD5.

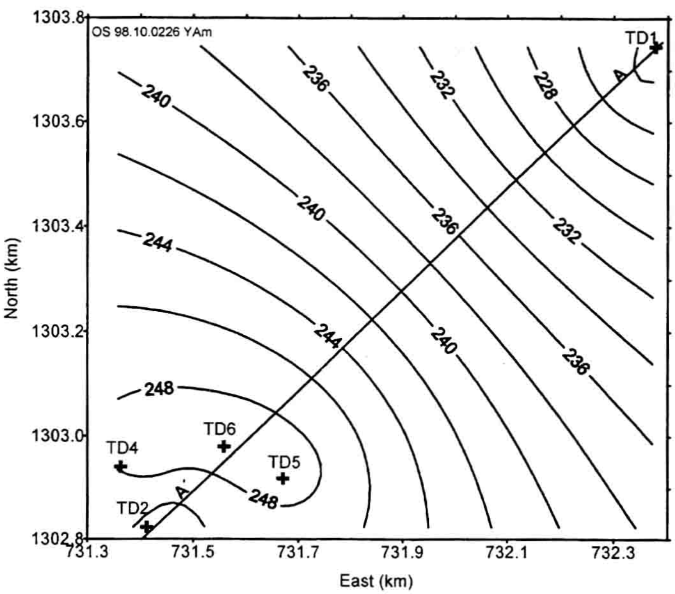

FIGURE 16: Temperature contours at 450 m depth