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INITIAL TEMPERATURE DISTRIBUTION IN THE MOMOTOMBO GEOTHERMAL FIELD, NICARAGUA

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ABSTRACT

An analysis and interpretation is given of the initial temperature distribution in the Momotombo high temperature field, Nicaragua, Central America. The study was based fundamentally on more than 500 downhole temperature measurements and a mineralogical study of 1/3 of the wells. A database was used to estimate initial and alteration temperatures in each well. Then temperature cross and plane sections of the field were made which were analyzed for the construction of a conceptual model for the reservoir. The geothermal field is divided into two reservoirs. A hot deep upflow zone with a temperature range of 250-290°C, which is located in the western part of the field at >1000 m u.s.l. The deep reservoir feeds a shallow and horizontal reservoir at 200-400 m u.s.l., which has a temperature range of 200-230°C. Both reservoirs are liquid dominated. An equilibrium between alteration and initial temperature seems to exist in most of the wells analyzed. However, in the southeastern part of the field are signals of natural cooling, observed as inflow of <100°C water into the geothermal system. The areal extent of the deep reservoir is unknown to north and west. Future drilling should be directed to this part of the field as the geothermal reservoir has not yet been bounded by drilling in these directions.

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INTRODUCTION

This report is the final part of a six month long training course given by the United Nations University (UNU) Geothermal Programme. The training took place at the UNU department which is situated in Reykjavik at Orkustofnun (National Energy Authority) in Iceland.

The training was divided into a theoretical and a practical phase. The first stage began on May 2 and finished on June 4, with lectures about geothermal energy in the world, planning of geothermal projects, geological exploration, borehole geology and alteration mineralogy, hydrology and hydrogeology, introduction to computers, geophysical exploration, borehole geophysics (logging), reservoir models, chemistry of thermal fluids, environment and process utilization, low temperature utilization, high temperature utilization, drilling technology, well design, cementing and maintenance, and guidelines for writing reports.

The second part of the course began in June and concentrated on lectures about reservoir engineering. Before the start of the practical phase, several trips to different geothermal fields in Iceland were carried out, which allowed us to see the extensive geothermal development of this beautiful country; also at this stage a technical report was written about which aspect of geothermal development it was thought necessary to pursue in accordance with the priorities of the home countries of the individual participants.

The present report is an analysis of the initial temperature distribution in the Momotombo geothermal field, based on temperature measurements carried out by General Direction of Geothermal Resources of the Nicaraguan Institute of Energy (INE), between 1976 and 1989. The temperature data were processed by computer, using the Grapher program to plot the temperature measurements. The results of alteration mineralogy served to deduce temperature profiles for several wells. Careful study of the temperature measurements and of the alteration data was used to estimate initial temperature in most of the geothermal wells drilled so far in Momotombo. This report is closely related to another UNU-report which is published simultaneously with this one (Gonzalez Barbosa, 1990a and 1990b). The preparation of these two reports required substantial work in data processing, which was performed in close cooperation by Mario and the author.

2 GENERAL INFORMATION ON THE MOMOTOMBO FIELD

2.1 Geothermal investigations in Nicaragua

Geothermal investigations started in Nicaragua in 1966. Between 1969 and 1973 an exploration program in the western country was carried out with the purpose of locating potential geothermal areas. It was determined that the Momotombo geothermal field was a potential area. Between 1974 and 1978 a first stage of drilling, and economic and technical feasibility studies for electrical generation were completed. The second stage of drilling and the construction of geoelectrical plant of 35 MW continued between 1981 and 1985. Between 1987 and 1989 a second 35 MW unit was installed. At present, there are 39 wells drilled there, of which 23 are productive, 5 are used for reinjection, and 11 for monitoring (Figure 1, Table 1). The geothermal development in Momotombo has received help from different countries and institutions such as the United Nations, Italy, France, Canada, Mexico, Iceland, Japan, and New Zealand.

2.2 Location and geology

Figure 1 shows an areal map of the Momotombo geothermal field. It is located on the hillside south of Momotombo volcano, which belongs to the Marrabios Cordillera that rises over the Nicaraguan Graben (Martinez Tiffer et al., 1988). The field is crossed by principal faults mostly in a NE-SW direction, but also in a NW-SE direction. A system of secondary faults extends N-S and E-W; the major density of ligaments passes through a sector containing the productive

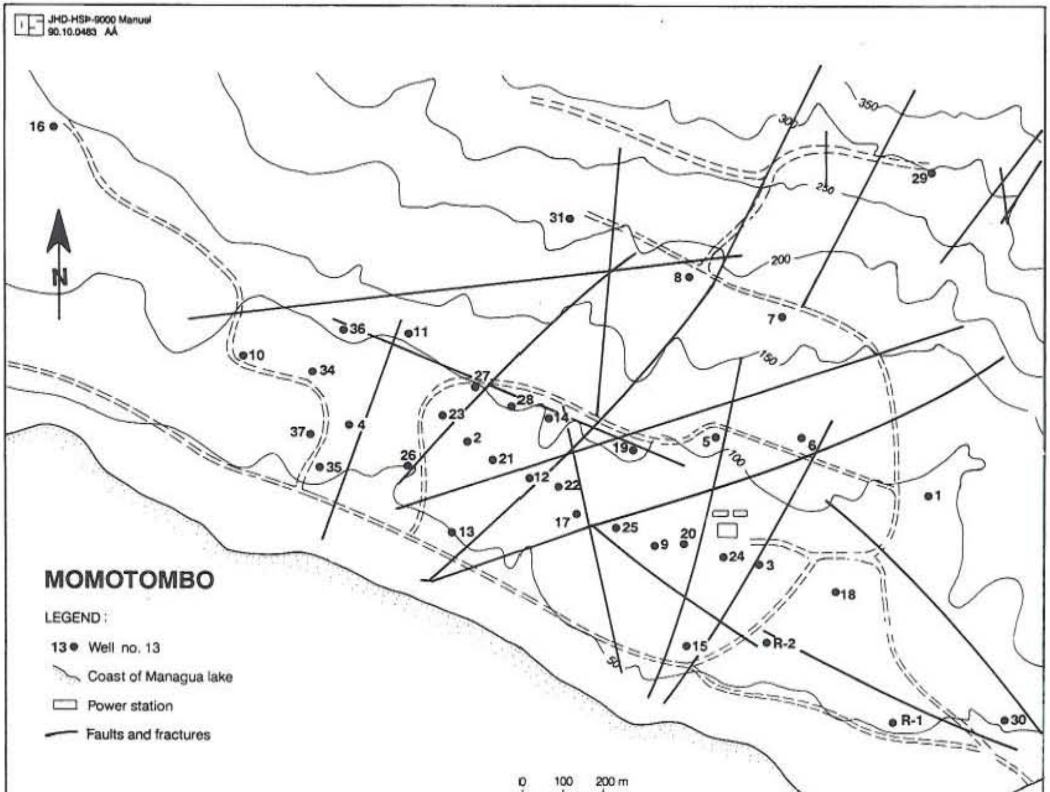

FIGURE 1: Areal map of the Momotombo Field and location of faults

TABLE 1: Overview of the Momotombo geothermal wells

Well Name	Completion Time (dd,mm,yy)	Depth (m)	Casing Depth and Diam. (m & ")	Liner Length and Diam. (m & ")	Coordinate X (m)	Coordinate Y (m)	Elevation (m)	Status of the well M: Mononitoring P: Production R: Reinjection
MT-1	27-01-75	1885	425-9,5/8		2567	642	100	M
RMT-1	08-12-82	1564	562-9,5/8		2113	15	57	M
MT-2	06-05-75	488	366-9,5/8	122-7	1338	745	60	P
RMT-2	17-02-83	1170	592-9,5/8	579-7	2146	235	63	R
MT-3		310	282-9,5/8		2122	44	74	M
MT-4	25-05-76	1450	684-9,5/8	766-7	1023	787	74	P
MT-5	01-12-75	1124	377-9,5/8	747-7	2000	775	106	P
MT-6	28-12-75	580	548-9,5/8	32-7	2228	784	109	R
MT-7	01-03-76	1798	595-9,5/8	899-7	2163	1082	175	M
MT-8	19-04-76	1757	949-9,5/8	729-7	1913	1190	83	P
MT-9	29-05-76	616	232-13,3/8	411-8,5/8				
MT-10	14-08-76	2104	760-9,5/8	1092-7	730	960	100	R
MT-11	13-01-77	1885	915-9,5/8	915-7	1180	1031	112	P
MT-12	03-10-76	402	234-13,3/8	168-9,5/8	1504	655	67	P
MT-13	18-12-76	1824	260-9,5/8	1564-7	1311	520	49	P
MT-14	03-11-76	670	243-9,5/8	405-9,5/8	1555	810	102	P
MT-15	05-12-76	649	261-9,5/8	388-7	1936	220	66	R
MT-16	14-03-77	2251	827-9,5/8		50	1812	106	M
MT-17	10-06-77	328	285-9,5/8		1632	567	71	P
MT-18	10-07-77	1124	256-9,5/8	748-7	2332	375	75	R
MT-19	30-07-77	536	259-9,5/8	265-7	1780	736	99	P
MT-20	12-08-77	310	260-9,5/8		1922	490	80	P
MT-21	31-08-77	488	488-9,5/8	189-7	1413	702	71	P
MT-22	18-09-77	376	259-9,5/8	70-7	1582	635	70	P
MT-23	09-10-77	821	260-9,5/8	497-7	1274	815	71	P
MT-24	27-10-77	455	250-9,5/8	127-7	2025	460	83	P
MT-25	22-11-77	455	253-9,5/8	155-7	1734	530	73	P
MT-26	15-12-77	638	365-9,5/8	273-7	1179	680	49	P
MT-27	02-01-78	442	368-9,5/8		1365	896	87	P
MT-28	05-02-78	612	340-9,5/8	154-7	1458	840	93	P
MT-29	23-03-78	944	481-9,5/8	142-7	2578	1492	289	M
MT-30	17-05-78	1852	369-9,5/8		2785	27	52	M
MT-31	23-07-78	582	235-13,3/8		1602	1335	201	P
MT-32		934	234-13,3/8					
MT-34	30-05-83	985	516-9,5/8	469-7	923	925	86	M
MT-35	01-01-85	1300	603-9,5/8	160-7	932	932	56	P
MT-36	02-05-85	1653	650-9,5/8	250-7	1002	1033	97	P
MT-37		1650			916	758	71	P

wells (Figure 1). On the surface, the sector is formed by volcanic products such as lavic melts, pyroclastic and basaltic-andesitic breccia. The stratigraphy of the wells in the upper level is made up of colluvial and alluvial sediments which are backfill of the graben; the intermediate level contains materials belonging to the Sierra formation of the Pliocene-Pleistocene age; and the depth level is characterized by materials belonging to the Coyol formation of the Miocene age. The reservoir rock is formed by the lower level of the Sierra formation and by the permeable formation of the Tertiary age (Ferrey, 1977). Figure 2 shows surface alterations and fumaroles in the Momotombo field (Down and Sabatino, 1989).

2.3 Geochemistry

The geothermal reservoir is dominated by sodium-chloride type water. The chloride composition of the reservoir is approximately 3000 ppm and the silica of productive wells at atmospheric pressure is 550 ppm. The enthalpy varies between 1000 kJ/kg and 2800 kJ/kg. The percentage of gasses in proportion to steam is 1.1% in weight; of this proportion 90 % is CO_{2}. The recharges of the field are underground water, and not the Managua Lake, determined by deuterium contained in the water. There are no signals of early cooling of the reservoir (Quijano, 1989).

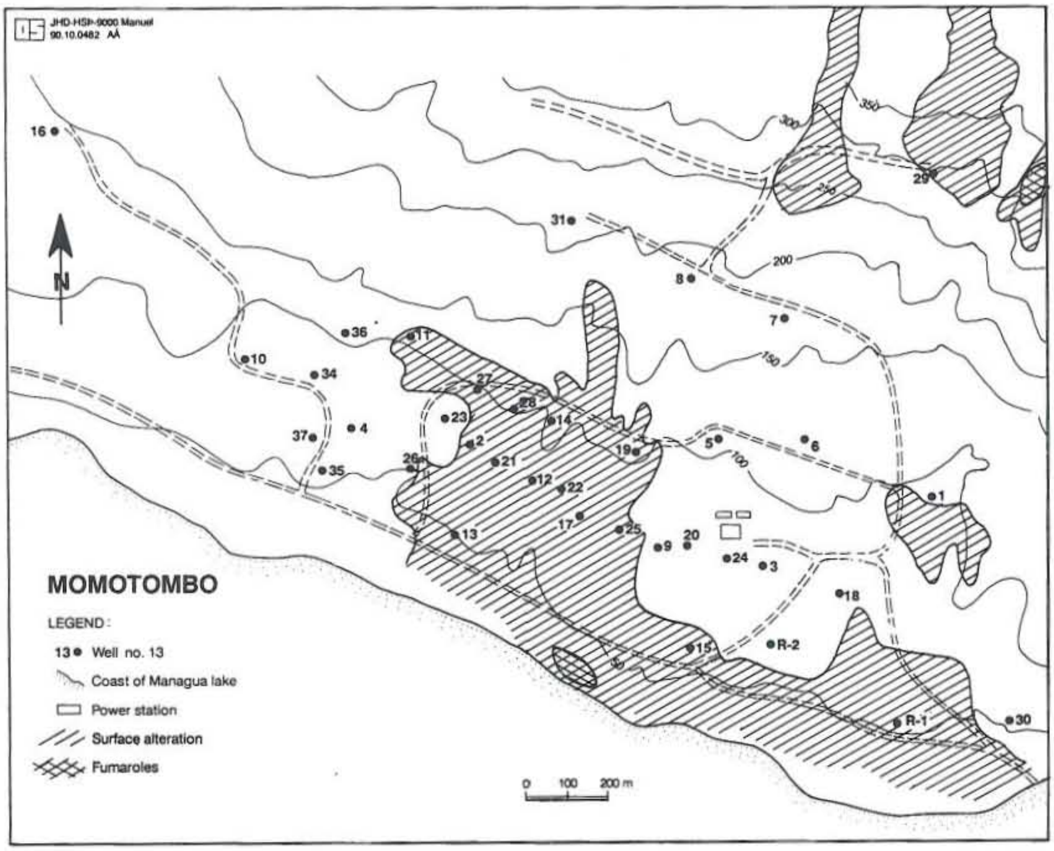

FIGURE 2: Surface alteration and fumaroles in the Momotombo field

2.4 Drilling of wells

Table 2 shows zones of loss circulation in 10 Momotombo wells (SPEG, 1989; Girelli et al., 1977; Recursos Geotermicos (INE), 1989). Drilling at Momotombo was carried out in two phases, from November 1974 to August 1978 and from October 1982 to October 1984. The drilling and completion techniques adopted at Momotombo are similar to those applied in oil wells, however, special cementing additives had to be used (Martinez Tiffer et al., 1988). The permeability around wells and in bigger areas was determined by injectivity and interference tests (ELC, 1983). The wells drilled are between 310-2251 m deep and most of them are concentrated in the mid-west sector of the field.

TABLE 2: Circulation losses in Momotombo wells (depth in well coordinates)

Well	Upper reservoir	Deeper reservoir
MT-1	212-244, 507-776	
MTR-1	562-800	
MTR-2	611-635, 1094-1120, 1120-1170*	
MT-2	378*	
MT-3	298*	
MT-4		1233-1395*
MT-13		346-398
MT-35		1130, 1220, 1300*
MT-36		700-1100*, 1200-1350
MT-37		1100-1150

* Total loss of circulation.

From: SPEG (1989); Girelli et al. (1977); Recursos Geotermicos (INE) (1989).

3 INITIAL TEMPERATURE OF THE MOMOTOMBO WELLS

3.1 General Approach

The initial temperature curves considered in this study were generated by the following procedures:

a) by plotting all available temperature measurements from a well on the same graph.
b) taking initial surface temperatures in the range of 50-100°C.
c) checking bottomhole temperatures with time, and using the average value as the initial temperature at that depth (but excluding measurements made right after drilling).
d) checking depth sections where several temperature measurements show all concave or convex behaviour (local minimum and maximum). Initial temperatures were always drawn through these intervals.
e) by analyzing mineral alteration in the wells, and plotting an "alteration temperature" interval on graphs with the measured temperatures.

A smooth curve was drawn when all the above checkpoints were available, on a depth-temperature graph, that was able to pass all the depth intervals where the initial temperature was speculated to be. This curve was then digitized and stored in a simple PC database for further processing. A detailed description of this database is given by Gonzalez Barbosa (1990).

Table 3 shows what was considered to be the characterizing temperature for the individual minerals found in the Momotombo wells (Steingrimsson et al., 1986; Arnorsson, 1979; More, 1989; Browne, 1978; Franzson, pers. comm.; Fridleifsson, 1983). The "Alteration Temperature" for a mineral is usually given within a temperature range. In this study, an average was used. These average values are given in Table 3. The drill cutting analysis was made by the Geological Service of Sweden (1990).

TABLE 3: Deposition Temperature of some Minerals

Mineral	Estimated temperature of deposition °C
Cristobalite	120
Kaolinite	140
Tridimine	150
Laumontite	160
Montmorillonite	160
Quartz	180
Feldespars	200
Chlorite	220
Swelling-chlorite	220
Analcime-wairakite	220
Illite	215
Pyrite	220
Smectite	200
Fe-chlorite	220
Calcite	230
Epidote	260

3.2 Description of initial wellbore temperatures

Figure 3 shows initial temperature profiles for the wells studied. In Appendix A are shown initial temperatures for each well, along with alteration temperature (if available). Table 2 shows circulation loss zones for some wells drilled in the field. It is evident from this study and others that the Momotombo reservoir is divided into a shallow reservoir and a deep reservoir (Martinez Tiffer et al., 1988; Girelli et al., 1977). In the following text, a detailed description is given for both wells in the shallow reservoir and in the deep reservoir.

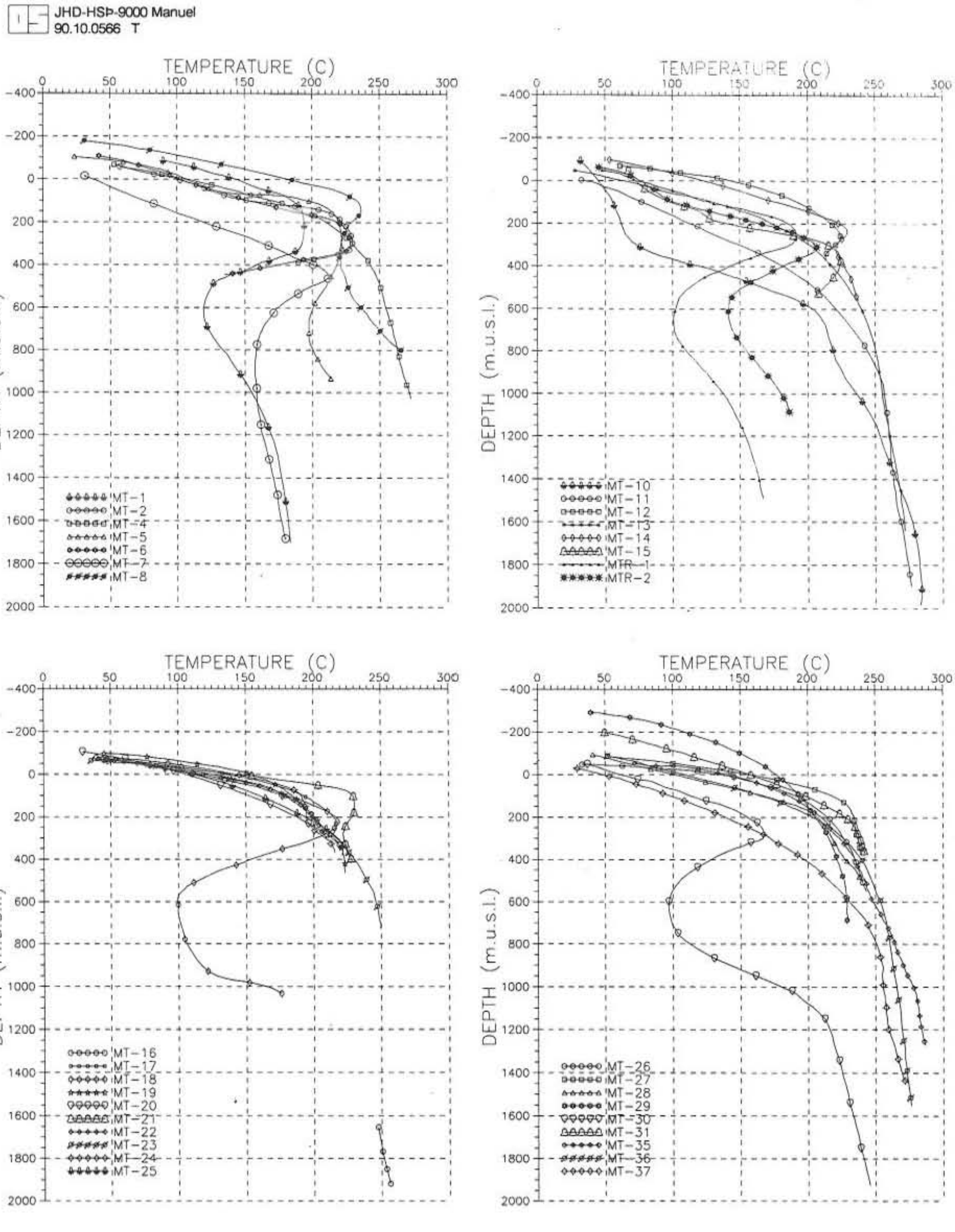

FIGURE 3: Initial temperature of some Momotombo wells

3.2.1 Shallow Reservoir Wells

Well MT-1: This well is 1885 m deep, with an initial bottom temperature estimated to be 185°C. A temperature maximum is found between 300 and 400 m depth. Between 400 and 800 m depth the temperature decreases to 120°C, possibly showing the existence of a cooling flow. The temperature increases below 800 m depth. During its drilling the well encountered circulation losses between 212 and 244 m depth and from 507 to 1776 m depth (Girelli et al., 1977). The mineralogical results detect the presence of quartz, wairakite, limonite, calcite, chlorite; the deposition temperature was estimated to be between 180 and 230°C for these minerals. The samples were taken at 100 and 300 m depth. In this depth range, there seems to be an equilibrium between reservoir and alteration temperature.

Well MTR-1: This well is 1564 m deep, with an initial bottom temperature estimated to be 165°C. A temperature maximum is found between 250 and 350 m. The temperature decreases at 400 m from 190 to 105°C at 800 m, where it starts to increase again.

Well MTR-2: This well is 1170 m deep, with an initial bottom temperature estimated to be 185°C. Between 250 and 400 m depth a 190-200°C temperature maximum is found. From 400 to 600 m the temperature decreases to a 145°C low.

Well MT-2: This well is 488 m deep, with a 190°C initial bottom temperature. The average temperature for the hot zone at 250-450 m depth is approximately 220°C. During drilling, a total circulation loss occurred below 378 m depth (Girelli et al., 1976).

Well MT-5: This well is 1124 m deep, with an initial bottom temperature of 215°C. The permeable strata is between 250 and 350 m depth, with an average temperature estimated to be 225°C. Below 350 m, the temperature drops to about 195°C at approximately 700 m depth. From there, temperature increases again.

Well MT-6: This well is 580 m deep, with an initial bottom temperature estimated to be 140°C. Between 350 and 450 m depth the temperature is approximately 225°C. The temperature decreases to 140°C at 560 m depth.

Well MT-7: This well is 1798 m deep, with an initial bottom temperature estimated to be 180°C. A temperature maximum is found between 400 and 500 m depth, with an average of 215°C; then it decreases to 160°C at 1000 m depth, and from that depth the thermal gradient is positive again.

Well MT-8: This well is 1757 m deep, with an initial bottomhole temperature estimated to be 260°C. A hot flow zone is found between 500 and 600 m depth with an average temperature of 240°C; then the temperature decreases to 220°C at 900 m depth.

Well MT-12: This well is 402 m deep, with an initial bottom temperature estimated to be 230°C. A hot flow is located between 200 and 350 m depth with an average temperature of 220°C. From 91 to 390 m depth, the initial temperature and alteration temperature are in equilibrium; the alteration zone's temperature is at 160-230°C. The mineralogical samples show the presence of montmorillonite, stilbite, pyrite, illite, quartz, kaolinite, calcite, wairakite, and chlorite. The samples were taken at 91, 120, 182, 213, 335, and 390 m depth.

Well MT-14: This well is 670 m deep, with an initial bottom temperature estimated to be 235°C. A hot zone is found at 300-400 m depth with an average temperature of 225°C.

Well MT-15: This well is 649 m deep, with an initial bottomhole temperature estimated to be 205°C. Temperature maximum is found between 400 and 500 m depth with an average of 215°C; below 500 m, temperature decreases all the way to the bottom.

Well MT-17: This well is 328 m deep, with an initial bottomhole temperature estimated to be 225°C. Hot water zone is at approximately 300 m depth, with an average temperature of 225°C.

Well MT-18: This well is 1124 m deep, with an initial bottomhole temperature of 175°C. Temperature maximum is found between 200 and 300 m depth with an average of 210°C. Thermal inversion occurs below 300 m, where temperature decreases to 100°C at 800 m depth.

Well MT-19: This well is 536 m deep, with a 225°C initial bottom temperature. Temperature maximum is found between 350 and 400 m depth with an average of 220°C. The mineralogical samples show the presence of minerals such as cristobalite, montmorillonite, gypsum, potassium-alumine, quartz, chlorite, pyrite, and calcite; the samples were taken at 73, 152, 243, 426 and 493 m depth. The studied alteration zone has a 120-230°C temperature range; thus, initial and alteration temperature are in equilibrium between 73-493 m depth.

Well MT-20: This well is 310 m deep, with a 225°C initial bottomhole temperature. The alteration temperature of the well varies from 120 to 220°C, between 67-280 m depth; thus, it is in equilibrium with the initial temperature. The mineralogical samples show the presence of cristobalite, mixture layer, quartz, illite swelling-chlorite and montmorillonite; the samples were taken at 67, 182, and 280 m depth.

Well MT-21: This well is 488 m deep, with a 230°C initial bottomhole temperature. Temperature maximum is found between 300 and 400 m depth with an average of 220°C. The alteration temperature varies from 160 to 230°C. The mineralogical results detect the presence of quartz, pyrite, illite-montmorillonite, chlorite, analcime-wairakite and calcite. The samples were taken at 262, 451, and 481 m depth.

Well MT-22: This well is 376 m deep, with an initial bottom temperature estimated to be 210°C; there is no temperature reversal seen.

Well MT-23: This well is 821 m deep, with an initial bottom temperature estimated to be 255°C. A temperature maximum is found between 500 and 650 m depth. The analysis of the alteration temperature, which varies from 120 to 230°C, determines an equilibrium with the initial temperature within a 61-437 m depth. The mineralogical results detect the presence of minerals such as cristobalite, montmorillonite, epistilbite, pyrite, quartz, swelling-chlorite and calcite. The samples were taken at 61, 91, 152, 213, 365, and 437 m depth.

Well MT-24: This well is 455 m deep, with an initial bottom temperature estimated to be 215°C. A hot zone is found between 300 and 400 m depth with an average temperature of 205°C.

Well MT-25: This well is 455 m deep, with an initial bottom temperature estimated to be 220°C. A hot flow zone is found between 300 and 350 m depth with an average temperature of 205°C.

Well MT-26: This well is 638 m deep, with an initial bottom temperature estimated to be 250°C. Interference tests in this well detected the existence of two permeable barriers with an inflow estimated at 50% of the produced fluid (ELC, 1983). A hot flow zone is found between

400 and 550 m depth with an average temperature of 235°C.

Well MT-27: This well is 442 m deep, with an initial bottom temperature estimated to be 240°C. A hot flow zone is found between 300 and 400 m depth with an average temperature of 235°C.

Well MT-28: This well is 612 m deep, with a 240°C initial bottomhole temperature. A hot flow zone is found between 400 and 500 m depth with an average temperature of 225°C.

Well MT-29: This well is 944 m deep, with an initial bottom temperature estimated to be 230°C. A hot flow zone is found between 500 and 600 m depth with an average temperature of 210°C. The alteration temperature is between 120-230°C and seems to be in equilibrium with the reservoir temperature. The mineralogical results determine the presence of minerals such as cristobalite, tridimine, quartz, montmorillonite, pyrite, illite, gypsum, chlorite and calcite; the samples were taken at 61, 121, 201, 280, 402, 500, 597, 798, and 938 m depth.

Well MT-30: This well is 1852 m deep, with an initial bottom temperature estimated to be 242°C. It presents, as its main characteristic, a cooling flow between 400 and 1000 m depth, with an average temperature of 125°C. The temperature profiles, deduced from the mineralogical results, show that this sector of the field used to be of higher temperature; as the X-ray studies show the existence of cristobalite, illite, smectite, quartz, chlorite, pyrite, laumontite, calcite, epidote, and fe-chlorite. The deposition temperature for these minerals was estimated to be between 100 and 260°C. The samples were taken at 61, 115, 152, 285, 402, 522, 603, 707, 793, 1011, 1149, 1389, 1517, 1749, 1841 m depth.

Well MT-31: This well is 582 m deep, with an initial bottom temperature estimated to be 240°C. A hot flow zone is found between 350 and 500 m depth, with an average temperature of 230°C.

3.2.2 Deep Reservoir Wells

Well MT-4: This well is 1450 m deep, with an initial bottom temperature estimated to be 285°C. Good permeability with partial loss of circulation was found between 1233 and 1395 m depth (Girelli et al., 1977). The mineralogical results detect the presence of montmorillonite, swelling-chlorite, calcite, chlorite, and wairakite. The samples were taken at 152, 213, 394, and 1200 m depth. The alteration temperature seems to be in equilibrium with the estimated initial temperature curve.

Well MT-10: This well is 2104 m deep, with an initial bottom temperature estimated to be 280°C. The alteration temperature shows natural cooling at 400-700 m depth. The mineralogical results determine the presence of analcime-wairakite, quartz, cristobalite, calcite, montmorillonite, tridimine and pyrite. The deposition temperature for these minerals is estimated to be between 120 to 230°C. The samples were taken at 380, 424, 499, 610, 695, 793, and 2078 m depth.

Well MT-11: This well is 1885 m deep, with a 280°C bottomhole temperature. A temperature maximum is found between 1100-1300 m depth, with an average of 260°C.

Well MT-13: This well is 1824 m deep, with an initial bottom temperature estimated to be 275°C. During drilling, circulation losses from 346 until 396 m depth were observed (Well diagram MT-13). That indicates a feedzone with an average temperature of 235°C. Between 650 and 800 m depth is another indication of a feedzone with an average temperature of 240°C. The alteration temperature shows high values, 180-230°C, which indicate equilibrium with the initial temperature. The mineralogical results detect the presence of quartz, chlorite, alumine, illite, pyrite, calcite, and wairakite; the samples were taken at 457, 1188, 1420, 1743, and 1810 m depth.

Well MT-16: This well is 2251 m deep. Very little data is available from this well, despite its critical location as a boundary well of the field. The three measurements performed in the well after drilling indicate a minimum bottomhole temperature of 250°C, if the warm-up rate is taken into account. No data was found for the upper part of the well.

Well MT-35: This well is 1300 m deep, with an initial bottom temperature of 285°C. During drilling, a total loss of circulation occurred from 1287 m depth (SPEG, 1989). The mineralogical results detected the presence of cristobalite, quartz, illite, calcite, pyrite, and wairakite; the range of deposition temperatures for these minerals was estimated to be between 120 and 230°C. The samples were taken at 60, 165, 200, 280, 500, 600, 705, 815, 905, 1030, 1035, 1130, 1215 and 1280 m depth. This indicates that the reservoir is warming up naturally, since the alteration temperature is much lower than the estimated reservoir temperature in the well.

Well MT-36: This well is 1653 m deep, with a 277°C initial bottomhole temperature. During drilling a total circulation loss occurred between 700 and 1100 m depth and partially between 1200-1350 m depth (SPEG, 1989). These zones of circulation losses are probably feedzones. The mineralogical results detected the presence of cristobalite, illite-smectite, quartz, illite, chlorite, gypsum, calcite, swelling-chlorite, fe-chlorite, and wairakite; the deposition temperature for these minerals was estimated to be 120 and 230°C. The samples were taken at 60, 130, 285, 410, 500, 600, 665, 1390, 1465, 1555, and 1640 m depth.

Well MT-37: This well is 1653 m deep, with an initial bottom temperature of 280°C. During drilling, a partial loss of circulation occurred between 1100 and 1150 m depth (SPEG, 1989). The alteration temperature shows equilibrium with the initial temperature. The mineralogical results detect the presence of cristobalite, smectite, illite-smectite, calcite, quartz, fe-chlorite, wairakite, pyrite, and chlorite. The deposition temperature for these minerals was estimated to be between 120 and 230°C. The samples were taken at 70, 120, 200, 285, 500, 620, 695, 770, 890, 990, 1090, 1203, 1300, 1400, 1495 and 1540 m depth.

4 TEMPERATURE DISTRIBUTION IN THE RESERVOIR

4.1 Temperature cross-sections

When all the estimated initial temperature profiles were drawn and digitized, considerable work was put into drawing several temperature cross-sections in the Momotombo reservoir. Figure 4 shows the location of these cross-sections, and Figures 6-15 present the temperature cross-sections drawn. The isolines shown are solid if they can be connected between wells with certainty, and dashed where their location is uncertain. It should be kept in mind that these sections are based on the interpretation of more than 500 downhole temperature profiles and several alteration analyses of drill cuttings, therefore making them relatively reliable.

Figure 5 shows the initial temperature distribution in cross-section 1, including wells MT-16, MT-31, MT-8 and MT-7. It shows an upflow zone that spreads towards well MT-16, and has a very sharp boundary between wells MT-8 and MT-7 in the southeast.

Figure 6 shows the initial temperature distribution in cross-section 2. A hot upflow zone is seen beneath well MT-27, that spreads laterally to the southeast at 200-400 m u.s.l. A layer of cold water (<140°C) exists under this horizontal reservoir. The shallow reservoir at 200-400 m u.s.l. seems to be bounded to the northwest by well MT-11.

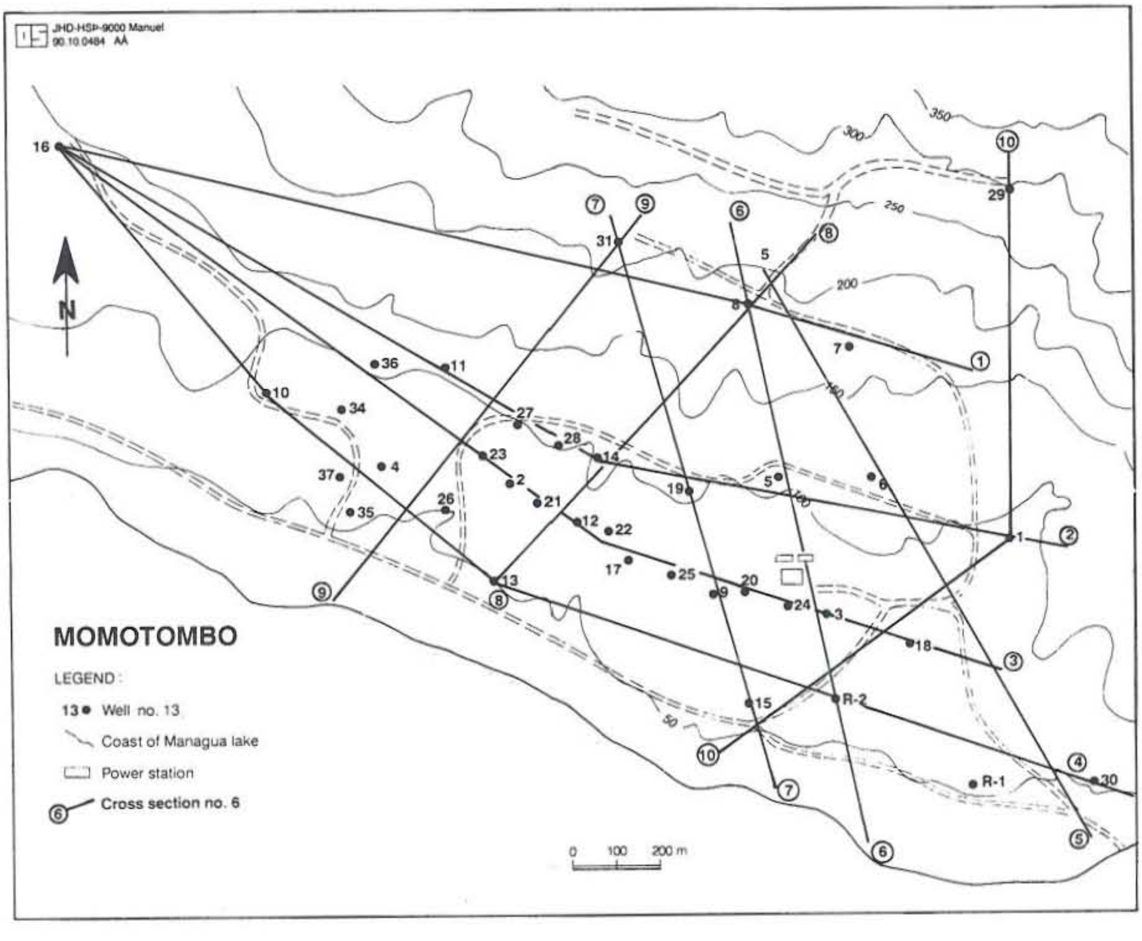

FIGURE 4: Location of temperature cross-sections in the Momotombo field

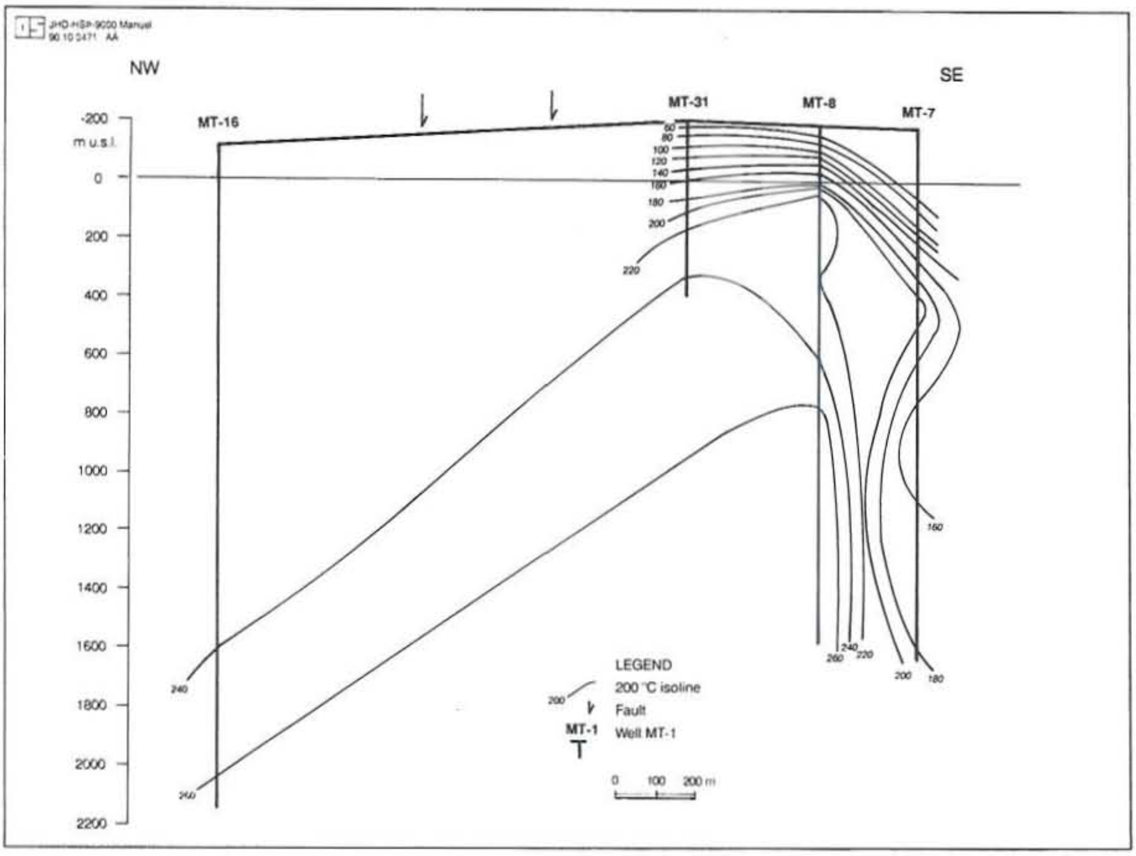

FIGURE 5: Temperature cross-section 1

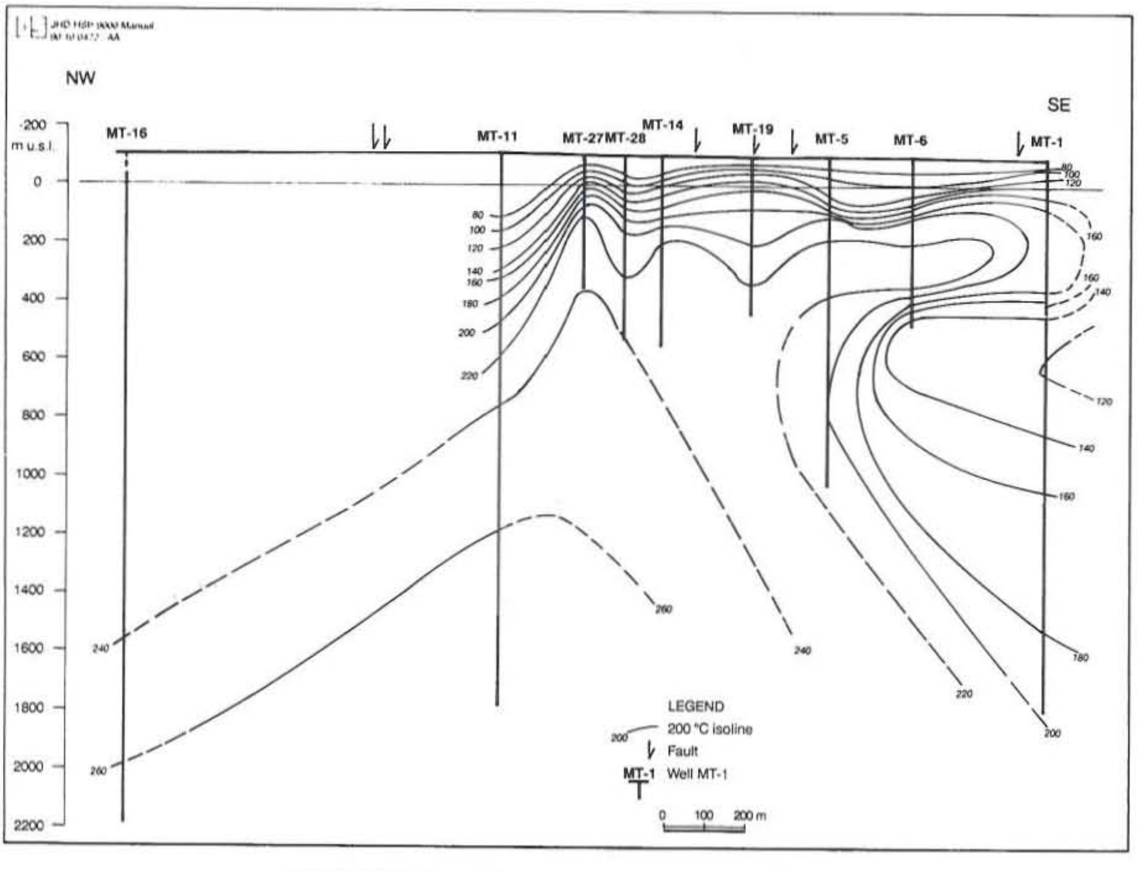

FIGURE 6: Temperature cross-section 2

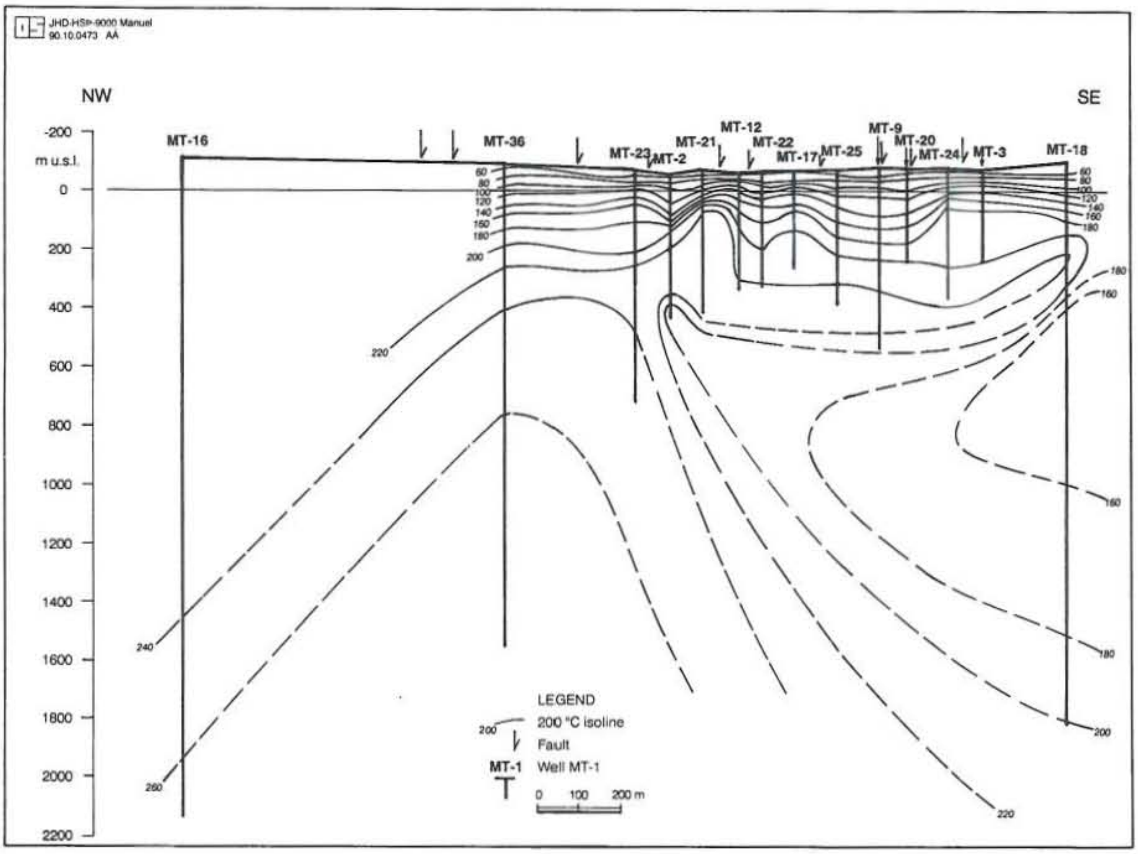

FIGURE 7: Temperature cross-section 3

Figure 7, which presents the temperature distribution in cross-section 3, shows similar characteristics as section 2, that is a deep and hot upflow zone under well MT-36 which spreads along a horizontal layer to the southeast at 200-400 m u.s.l. The same story is present in Figure 8, which shows temperature in cross-section 4. In this figure, it is also seen that the layer at 200-400 m u.s.l is bounded to the northwest by well MT-10. Another remarkable feature is the less than 100°C reservoir temperature observed in well MT-30. As the study of mineral alteration shows that reservoir temperature used to be much higher in this part of the field, it can be concluded that inward migration of a cooling front is taking place naturally in this part of the reservoir.

Figure 9 shows the temperature distribution in cross-section 5, which is located on the eastern margin of the present well field. A hot upflow zone is seen under well MT-8, and a shallow layer of hot water spreads and ends close to well MT-30. The cold influx zone of well MT-30 seems to extend to wells MT-1 and MT-18. The steep temperature difference between wells MT-30 and MTR-1 (at 1000-2000 m u.s.l.) may be explained by a cold inflow that occurs vertically along a fault that is between the wells (Figure 1).

Figure 10 shows the temperature distribution in cross-section 6. The main characteristics in the section is the hot and shallow reservoir at 200-400 m u.s.l. with a possible upflow zone close to well MT-8. Figure 11, which presents the initial temperature in cross-section 7, also shows the same characteristics, but the lower end of the shallow layer is uncertain here due to the shallow depth of the wells in this section.

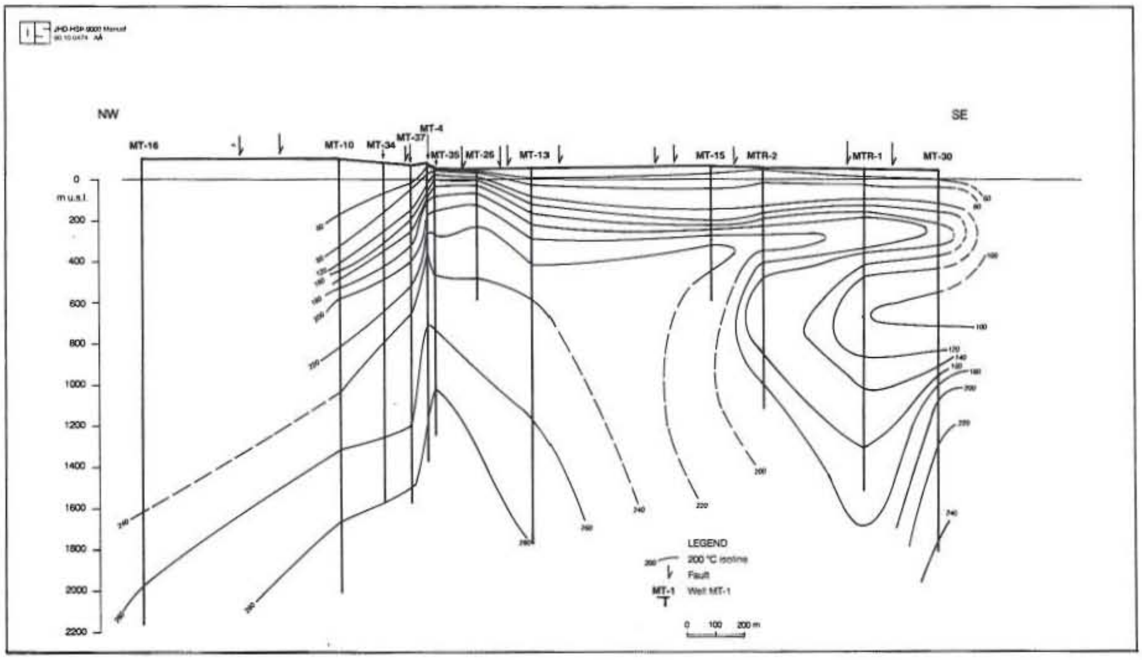

FIGURE 8: Temperature cross-section 4

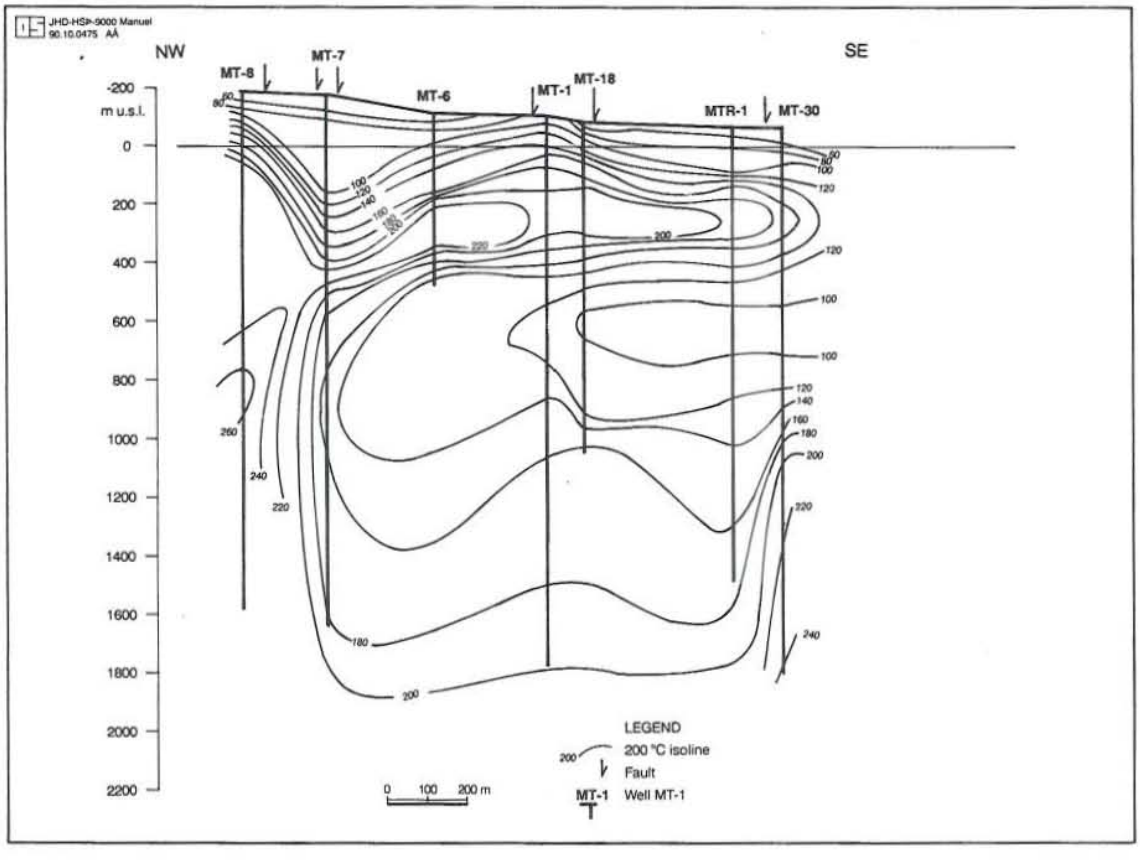

FIGURE 9: Temperature cross-section 5

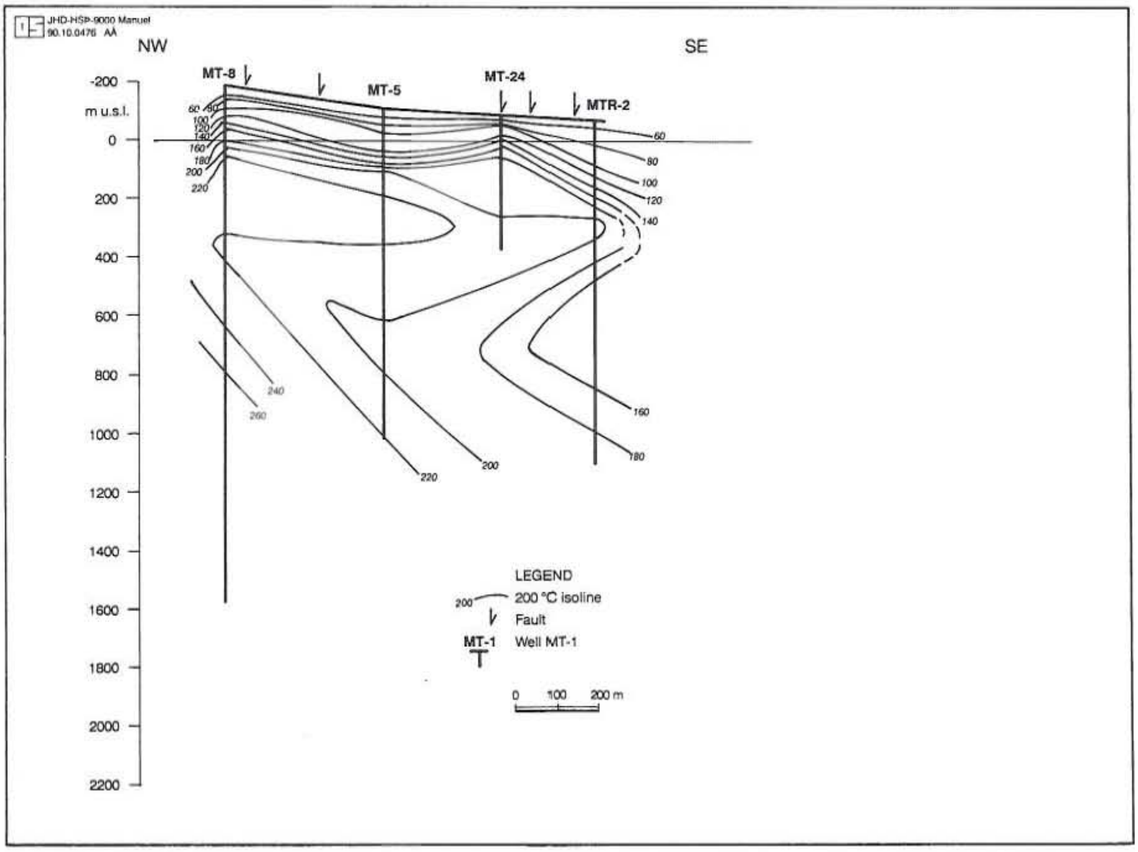

FIGURE 10: Temperature cross-section 6

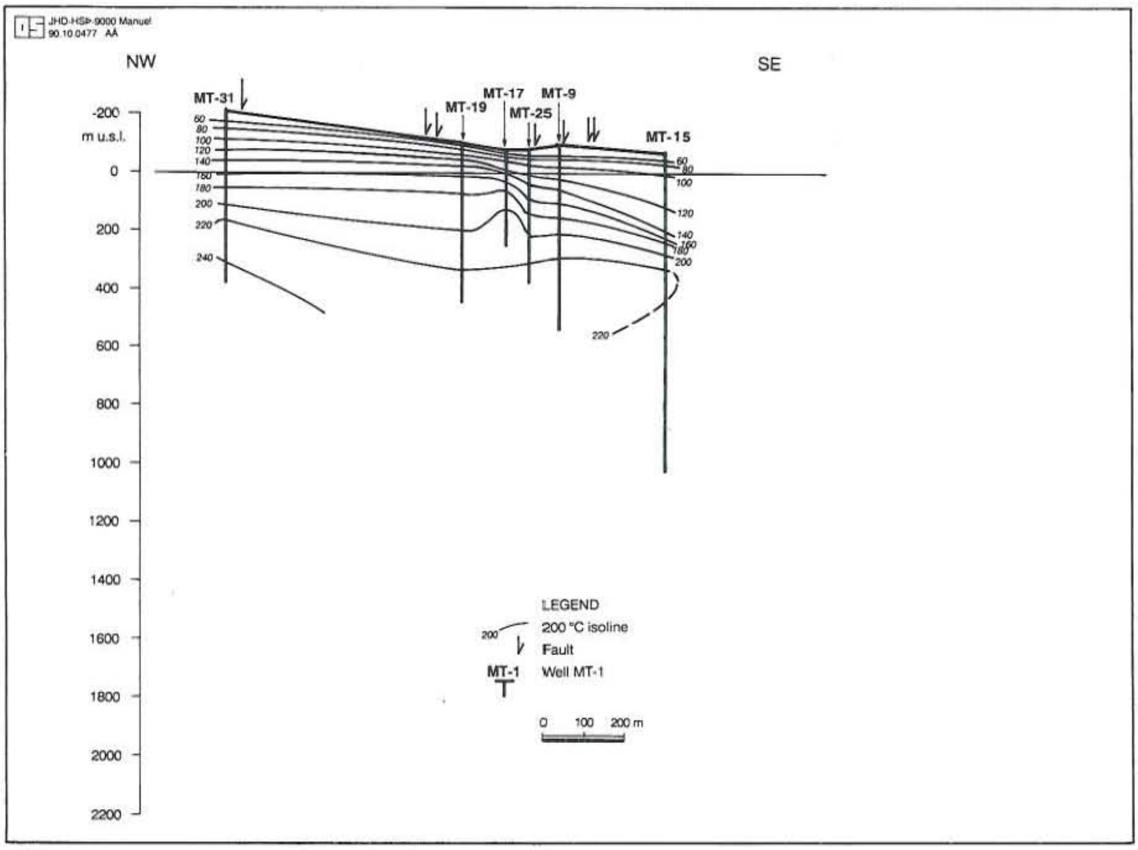

FIGURE 11: Temperature cross-section 7

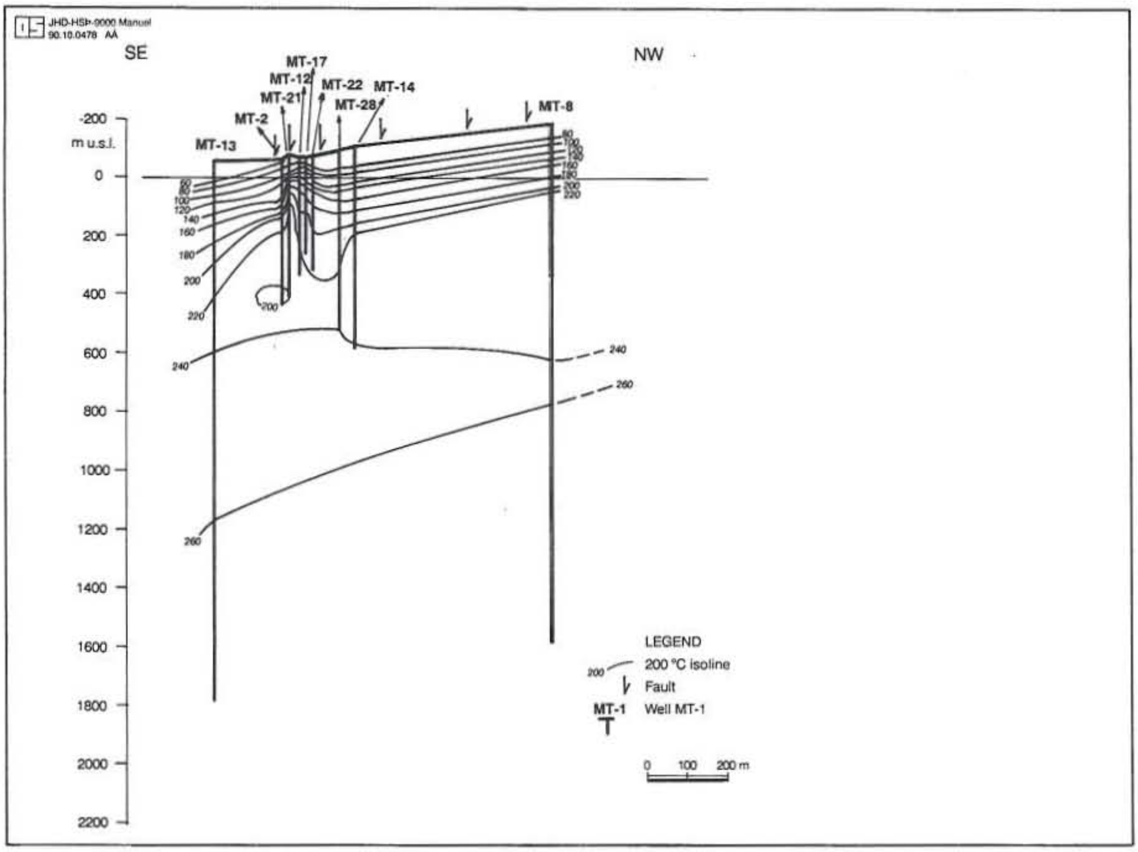

FIGURE 12: Temperature cross-section 8

Figures 12 and 13 show the initial temperature distribution in two parallel cross-sections (8 and 9) in the center part of the well field. The same characteristic is seen in both sections, a steep conductive temperature gradient in the uppermost 200-300 m of the reservoir, and then a gentler gradient as the wells pass into a convective hydrothermal system. Well MT-35 in section 9 presents the highest temperature observed in the Momotombo wells, >280°C. This indicates the vicinity of the potential inflow zone of the field.

Finally Figure 14 shows the estimated initial temperature distribution in cross-section 10. The section defines two possible upflow zones close to wells MT-5 and MT-29, and a lateral flow into a shallow layer at 200-400 m u.s.l. But the striking part of the section is a "tunnel" of cold inflow between wells MT-1 and MT-18. It is not clear how isolines shall be connected between wells in this part of the field. Figure 14 shows just one interpretation. Another possible way of connecting the isolines, is to draw the area of temperature <120°C up to the surface between wells MT-1 and MT-29. Whatever method is taken, it will not affect the primary conclusion of this section, which is the abnormally cold part of the reservoir between wells MT-1 and MT-18.

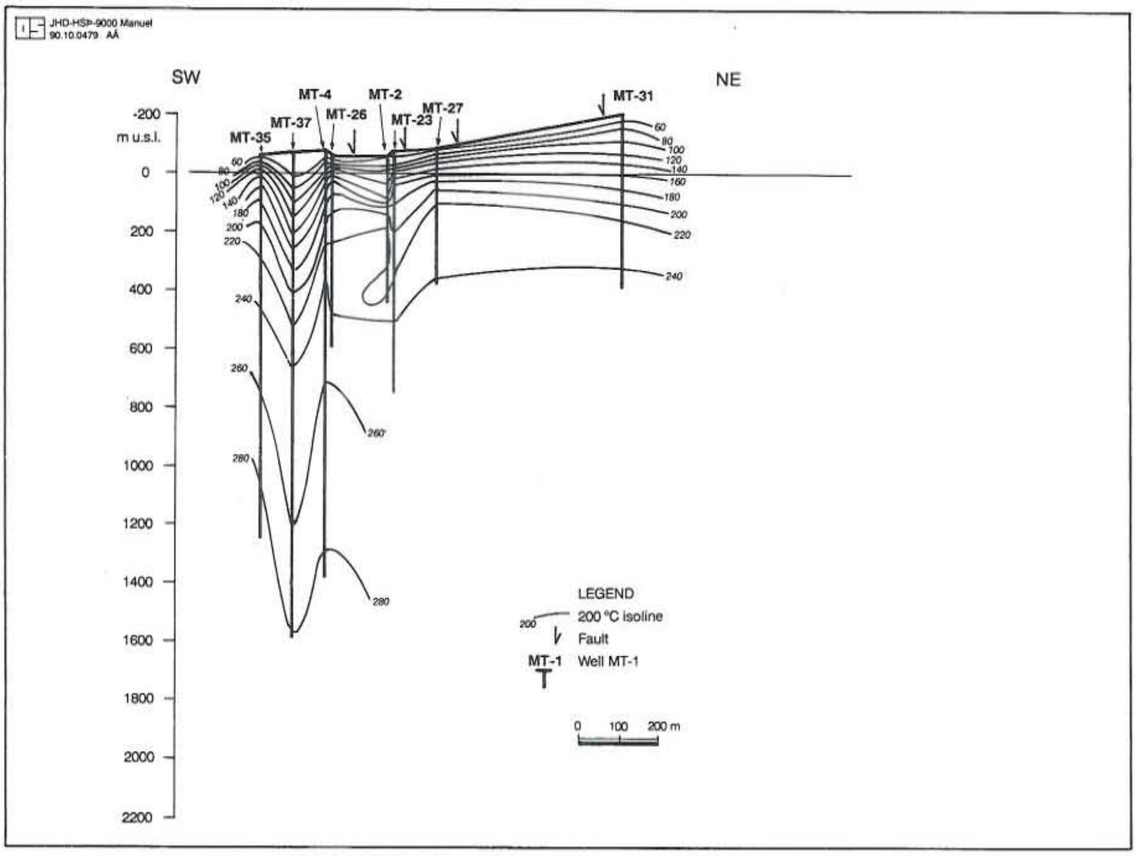

FIGURE 13: Temperature cross-section 9

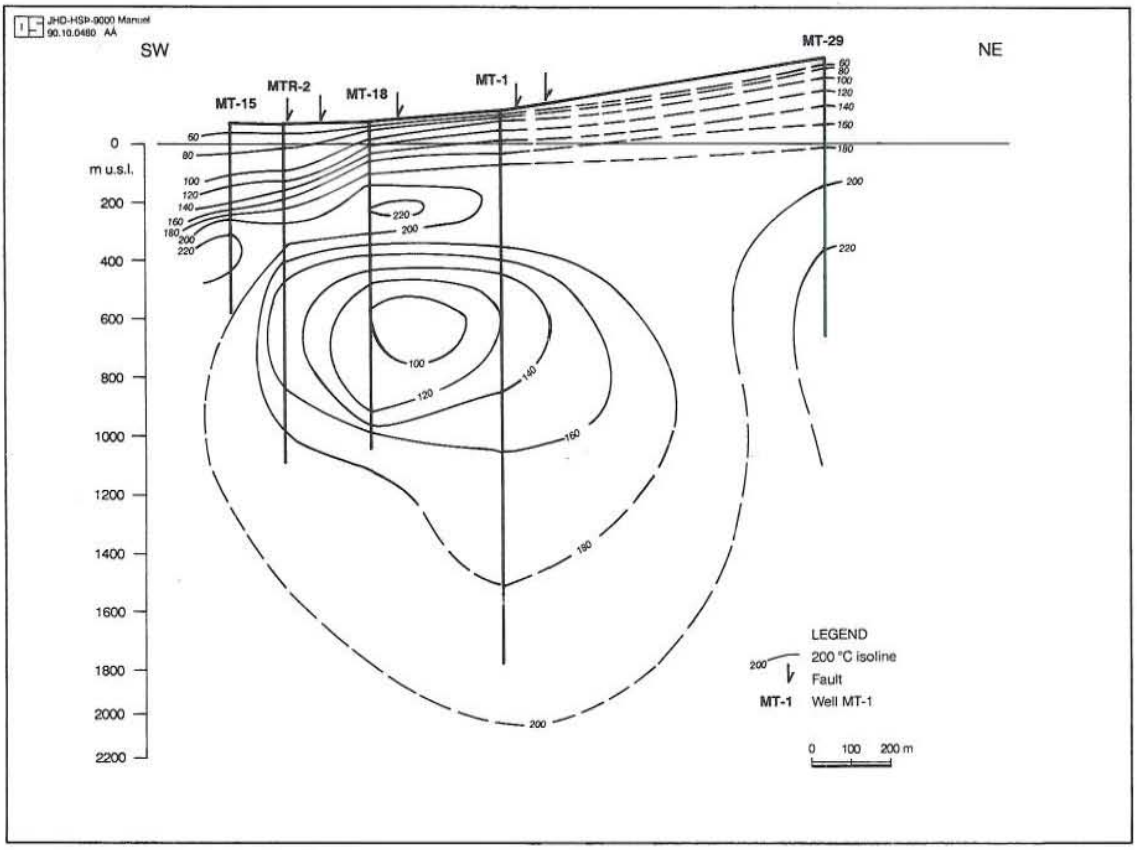

FIGURE 14: Temperature cross-section 10

4.2 Temperature plane-sections

Figures 15-18 show temperature plane-sections at 300, 500, 800 and 1000 m u.s.l. These figures are based on the estimated initial temperatures in the wells, but the temperature cross-sections described in the previous chapter, were also used for a reference in wells which are not deep enough for the elevation under consideration. As in the case of the cross-sections, isolines are drawn solid in areas of reliable information, and dashed where the exact location of the isoline is uncertain.

Figure 15 shows the initial temperature distribution at 300 m u.s.l. It shows clearly a lateral flow that spreads in easterly and southeasterly direction; its temperature varies between 200-230°C. Most of the wells intersect this layer of hot flow. This layer seems to be charged by inflow close to wells MT-4, MT-27 and MT-31. At 500 m u.s.l. (Figure 16) the temperature layer <200°C is of similar extent, but the cold inflow zone close to wells MTR-1, MT-18 and MT-30 is also seen. The potential inflow zone of hot fluid is, as previously, on a line between wells MT-35 to MT-31.

Figure 17 shows temperature at 800 m u.s.l. Here, the area of temperature >200°C has reduced a little, and the cold inflow zone is dominating in the southeast part of the wellfield. A hot upflow zone is well defined around wells MT-4, MT-8, MT-26, MT-35 and MT-31, where the temperature is >260°C. This upflow zone extend to the northeast, above well MT-29, and also further to the west. New wells and temperature data in well MT-16 may define the upflow area in more details.

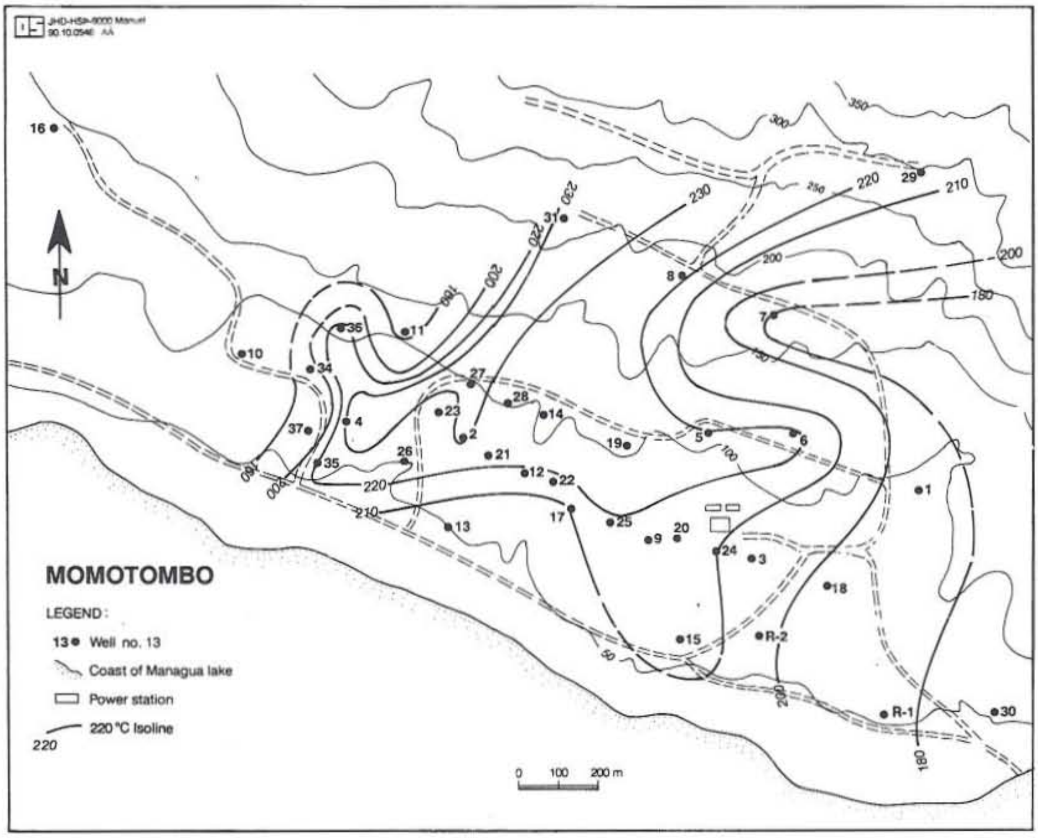

FIGURE 15: Initial temperature distribution at 300 m u.s.l.

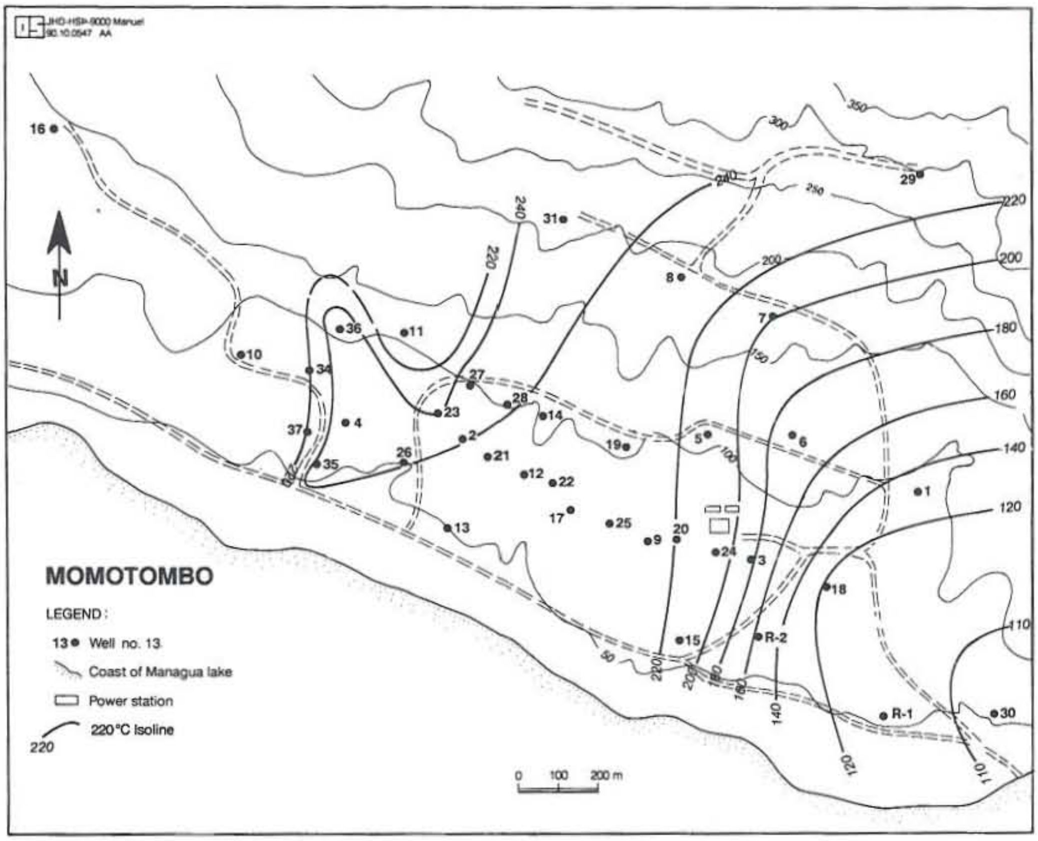

FIGURE 16: Initial temperature distribution at 500 m u.s.l.

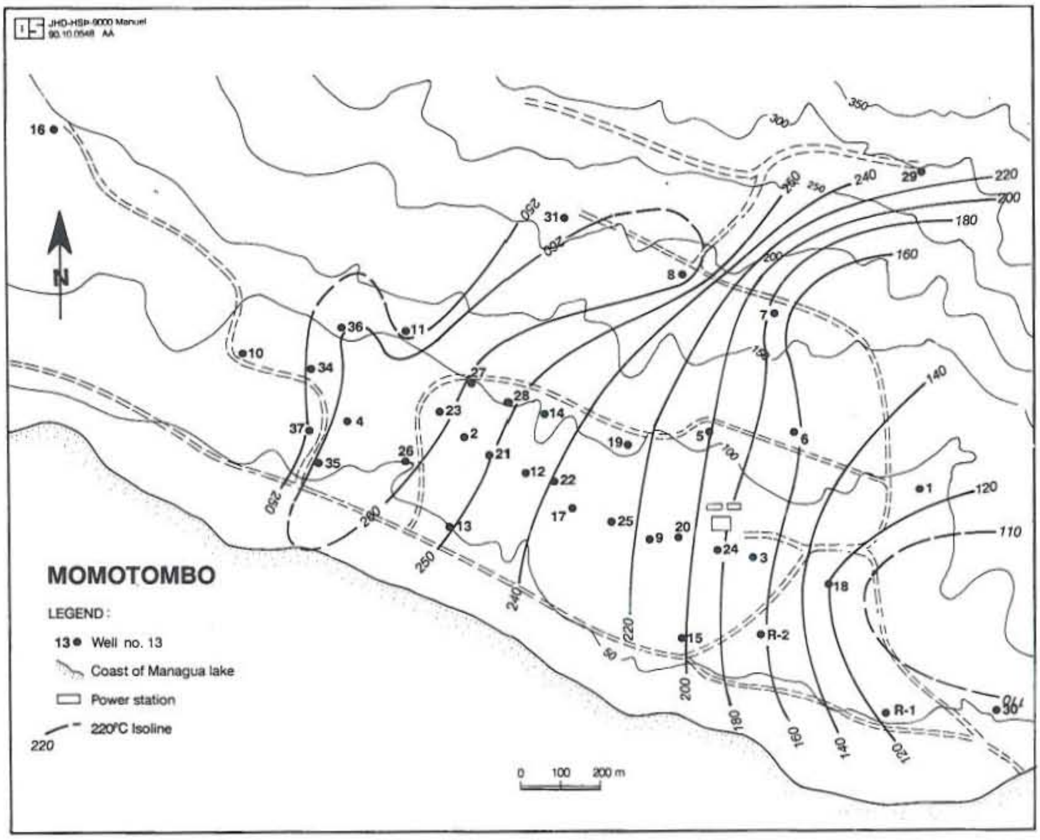

FIGURE 17: Initial temperature distribution at 800 m u.s.l.

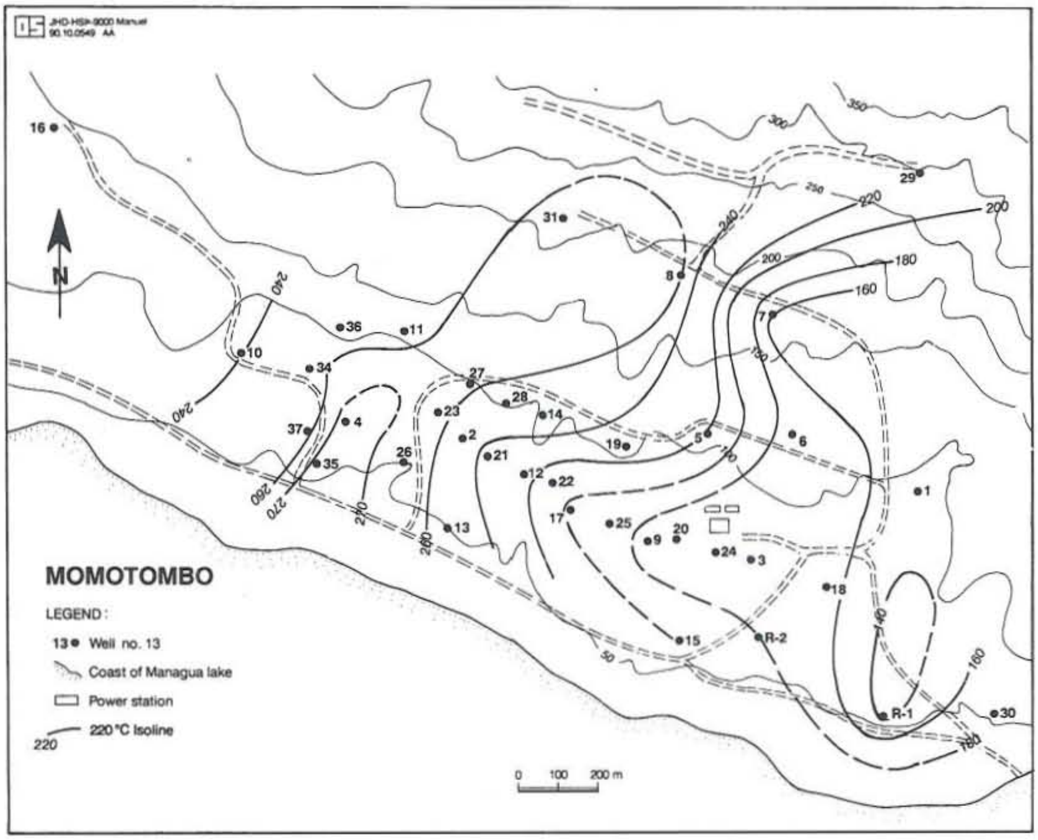

FIGURE 18: Initial temperature distribution at 1000 m u.s.l.

Finally Figure 18 shows the initial temperature at 1000 m u.s.l. The figure is similar in characteristics as Figure 17, but it should be kept in mind that most of the data points used to draw the figure are estimated by extrapolation, using the temperature cross-sections in chapter 4.1. The upflow zone is, as before, on a line between wells MT-31 and MT-35. There are indications that the hot reservoir extends into Managua Lake, rather than inland (to the north). The cold inflow zone is now bounded to the southeast, possibly showing effects of vertical faults on the flow direction.

5 CONCEPTUAL MODEL OF THE RESERVOIR

Hydrothermal convective systems are frequently associated with high temperatures and often show surface activity in the form of hot springs, fumaroles and surface alteration. A reservoir of liquid dominated origin is driven by a dynamic balance of mass and heat flow. Its temperature has, in some places, reached saturation conditions and the pressure is close to hydrostatic. The upflow at great depth presumably consists of water with high temperature; as the water rises, its pressure falls until it reaches saturation pressure. At this depth, the upflow continues towards the surface as a mixture of steam and water. In geothermal systems, the upflow is perhaps the main feature that distinguishes the system from its groundwater counterpart (Bodvarsson et al., 1986; Grant et al., 1982).

A conceptual model of a geothermal system is a descriptive or qualitative model of a system, that takes into account all the important processes that affect the system; it is the basic knowledge of the geothermal system and its behavior. It is used as a beginning point for resource evaluation and it contributes to establishing an adequate strategy for exploitation of the field.

The cross- and plane-sections in the previous chapter enables one to suggest the following conceptual model for the Momotombo geothermal reservoir (Figures 19 and 20).

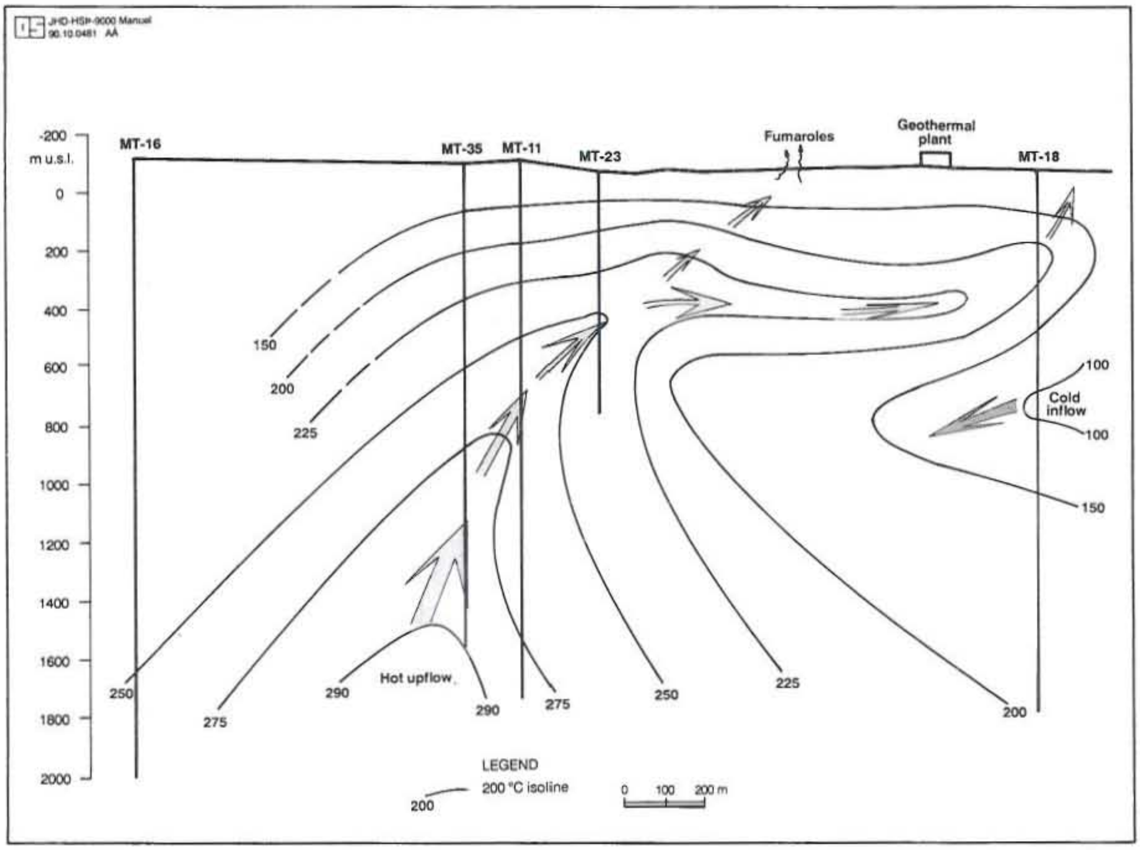

FIGURE 19: A conceptual temperature cross-section of the Momotombo field

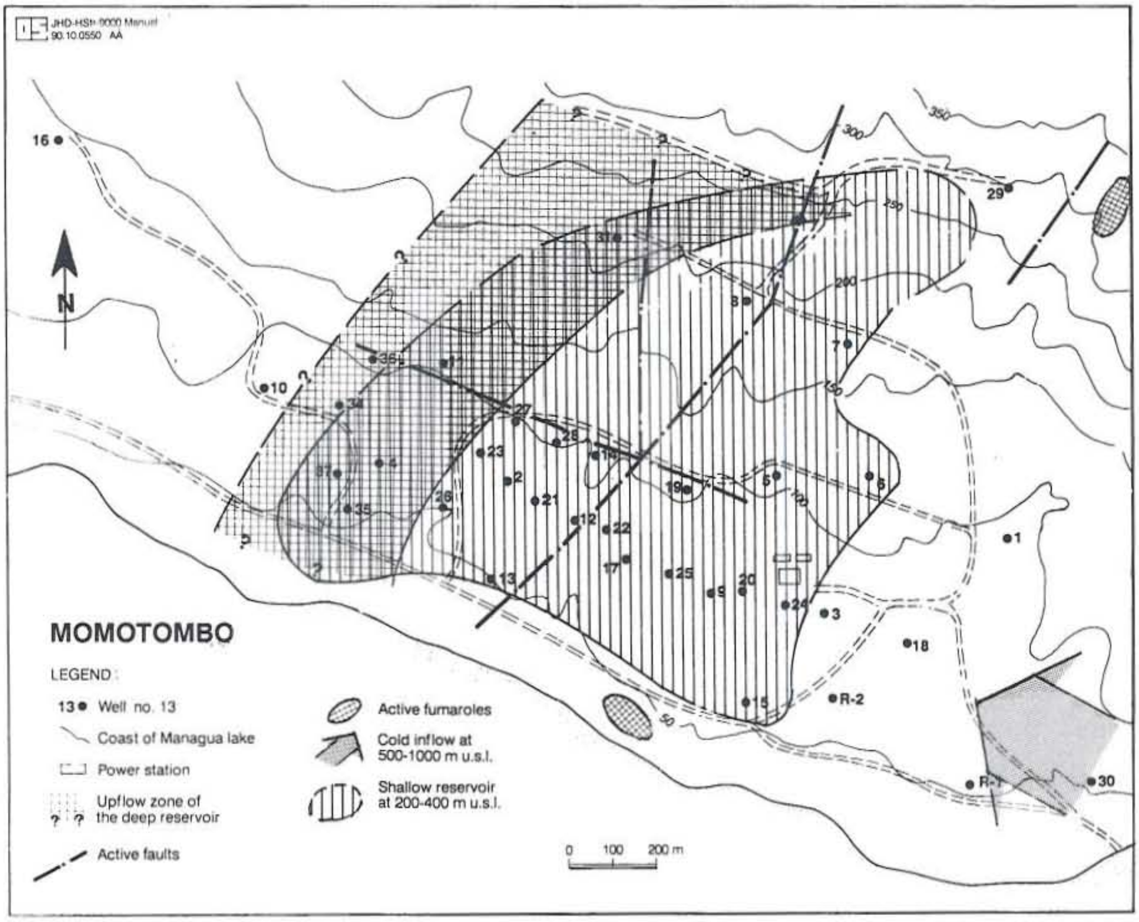

FIGURE 20: Areal extent of the shallow and the deep reservoir, active faults, fumaroles and direction of cold inflow

A hot (>280°C) near vertical upflow zone exists in the western part of the well field elongated in a NE-SW direction. As the hot fluid reaches 200-400 m u.s.l. elevation, it changes flow direction into a horizontal layer(s) of good permeability. The direction of the lateral flow is mostly to the southeast, and seems to be little or unaffected by faults. Most of the present Momotombo wells intersect and produce from this shallow reservoir.

A zone of cold inflow is found in the southeast part of the well field, beneath the shallow reservoir. Its temperature is 100-200°C. This cold zone is detected in several wells in the form of reversed temperature. A study of mineral alteration shows that this part of the field used to be hotter, but has cooled down naturally. Surface alteration shows that active hot springs and fumaroles were also of greater extent than today. This fact, in addition to the alteration studies in well MT-30, imply that the southeast part of the well field is in a natural cooling stage. The hot upflow area close to MT-35 shows, on the other hand, that this part of the field is in a warm-up stage. Active faults in the area may serve as channels for the near vertical upflow.

6 CONCLUSIONS AND RECOMMENDATIONS

The main conclusions of the study are as follows.

a) The Momotombo geothermal system consists of a deep and hot upflow zone, that is feeding a shallow horizontal reservoir at 200-400 m u.s.l.

b) The temperature of the deep reservoir is between 250-290°C, whereas the shallow reservoir is between 200-230°C.

c) There seems to be an equilibrium between alteration and initial temperatures in most of the wells studied. However, in the southeast part of the field, there are definite signs of natural cooling, indicating inflow of <100°C water into the geothermal system.

d) On the other hand, the upflow zone is warming up.

e) The extend of the deep reservoir is not known to the west and north. The hottest part is close to the coast of Managua Lake.

This study of the initial temperature distribution in the Momotombo geothermal field is incomplete. First of all there is the lack of temperature data in well MT-16, which would constrain the areal extent of the deep reservoir to the west. Measurements in wells MT-10 and MT-34 would also be of great help. The study of mineral alteration in wells should be completed and compared with the initial temperatures shown in this study. As the upflow zone seems to extend into Managua Lake, the bottom of the lake should be explored for possible signs of geothermal activity. It would also be interesting to drill new deep wells around and north of wells MT-29 and MT-31, in order to determine the extent of the deep reservoir to the north and west.

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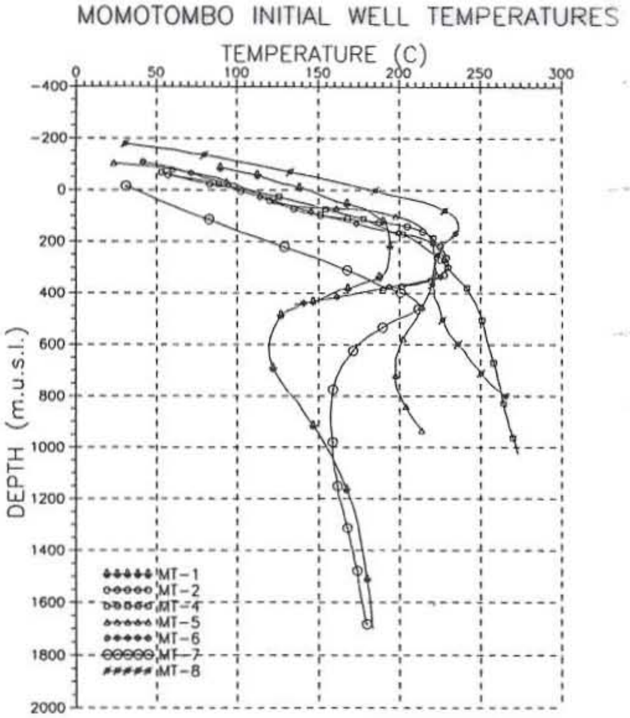
APPENDIX A:

Figures with initial temperature profiles, alteration temperature and some temperature measurements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-200
0
200
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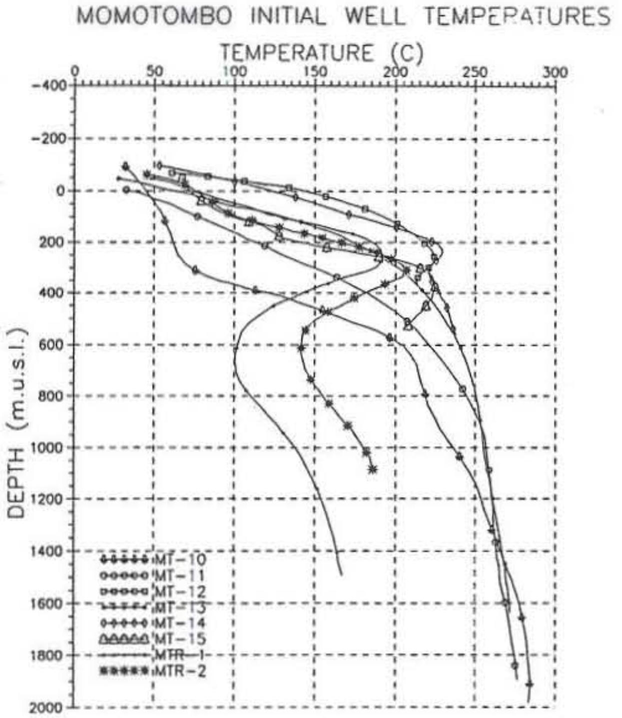
MT-1
MT-2
MT-4
MT-5
MT-6
MT-7
MT-8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800
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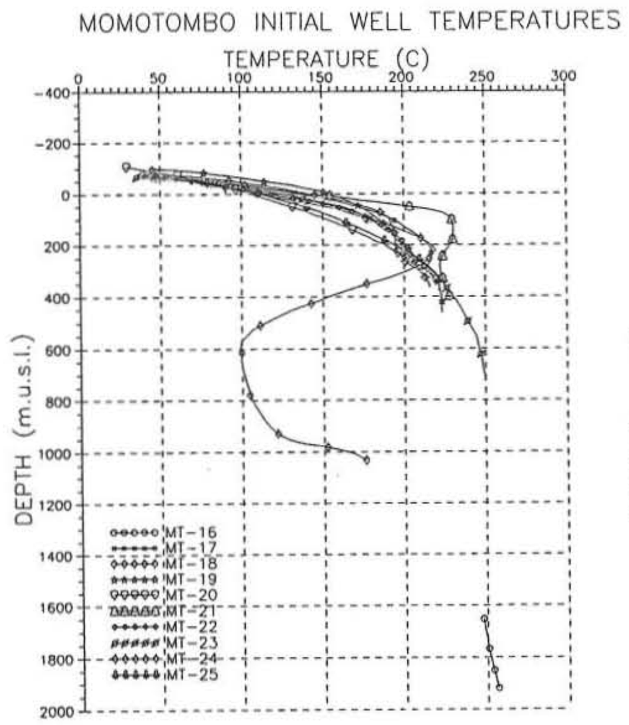
MT-10
MT-11
MT-12
MT-13
MT-14
MT-15
MTR-1
MTR-2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MT-21
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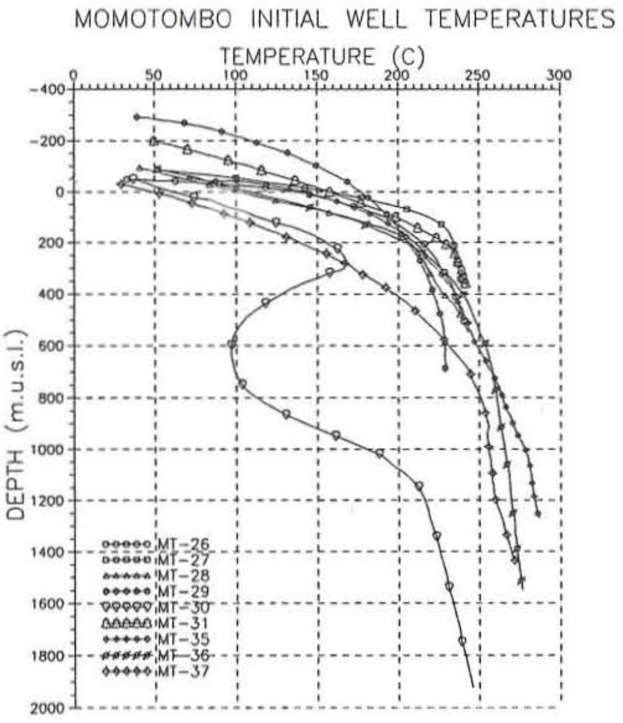
MT-25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MT-29
MT-30
MT-31
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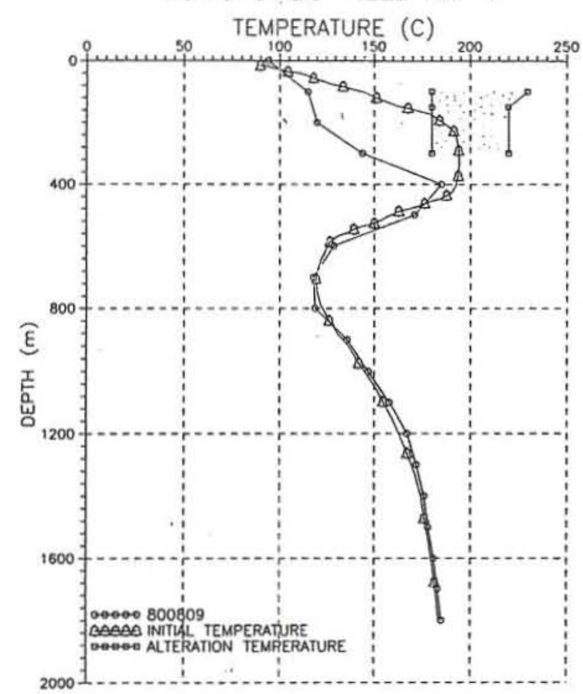
MT-36
MT-37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TEMPERATURE (C)
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DEPTH (m)
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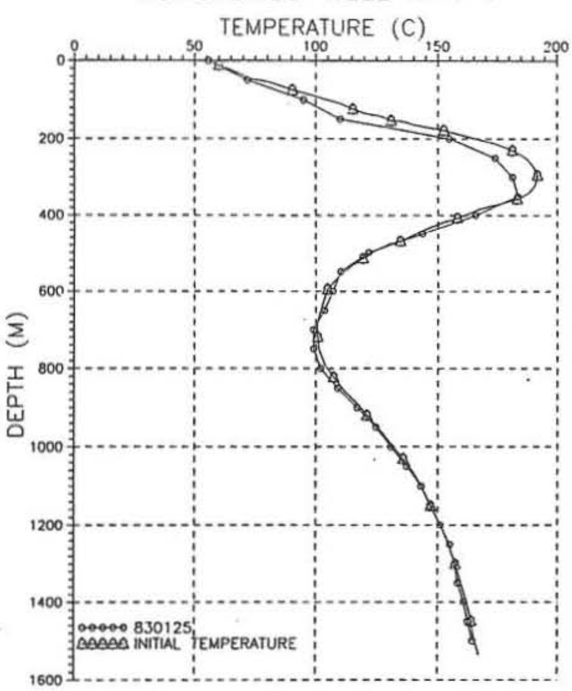
ALTERATION TEMPERATURE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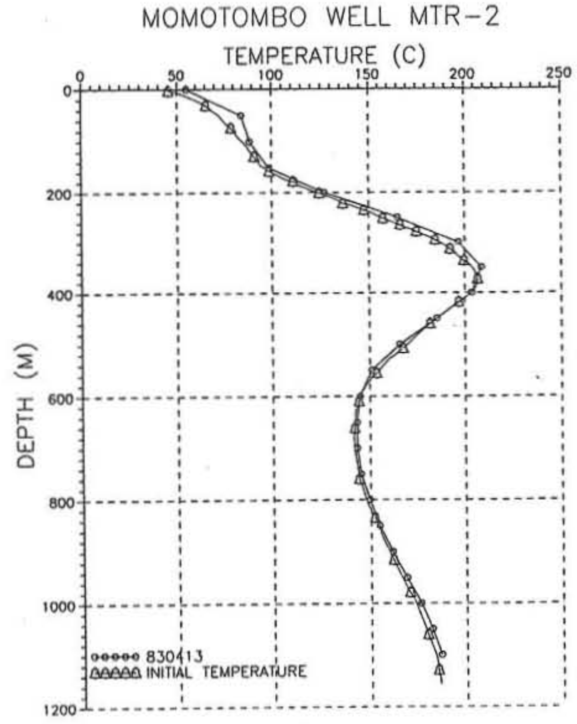
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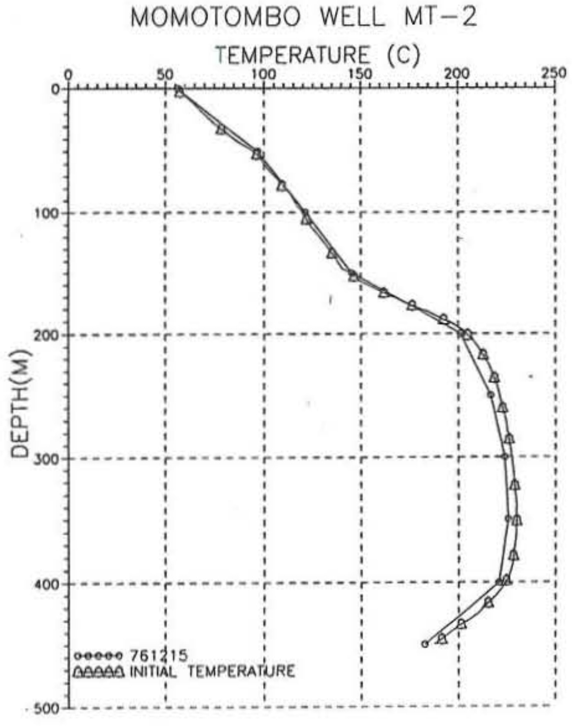
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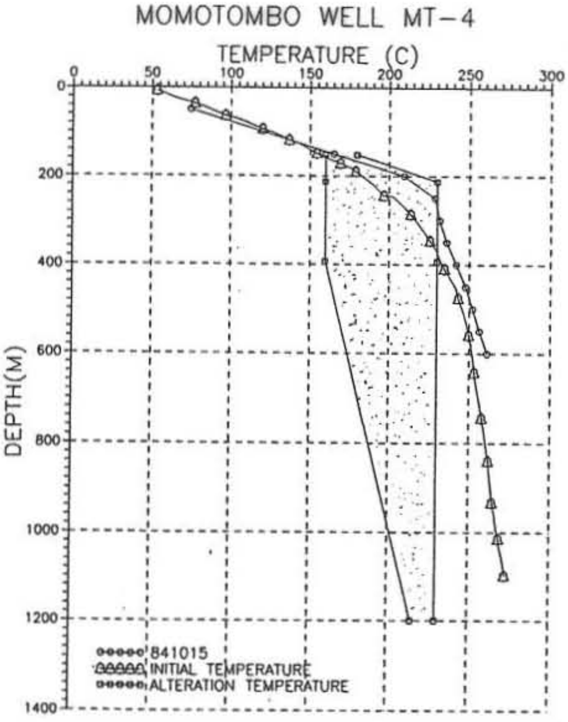
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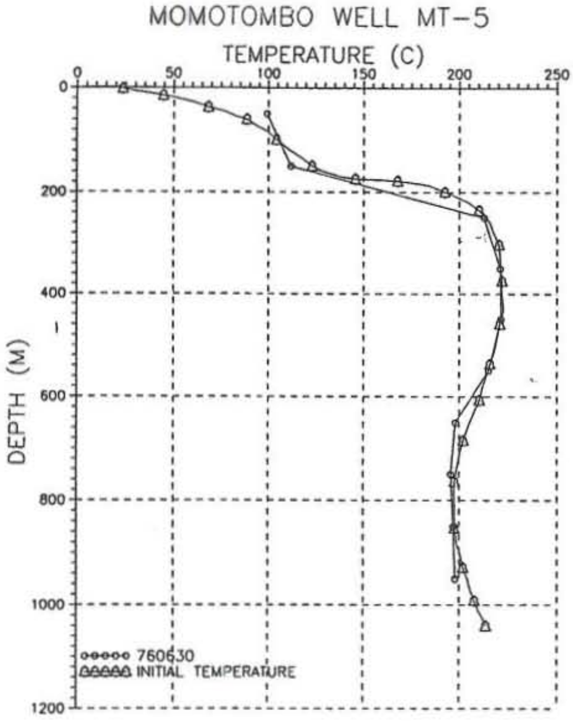
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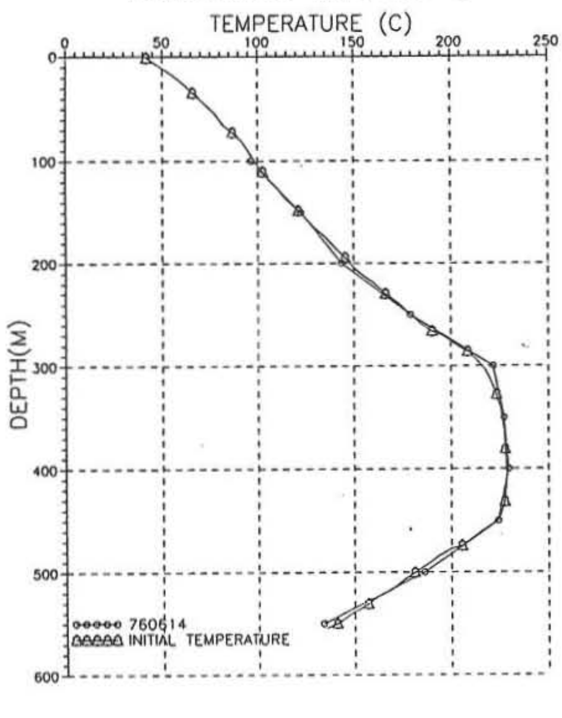
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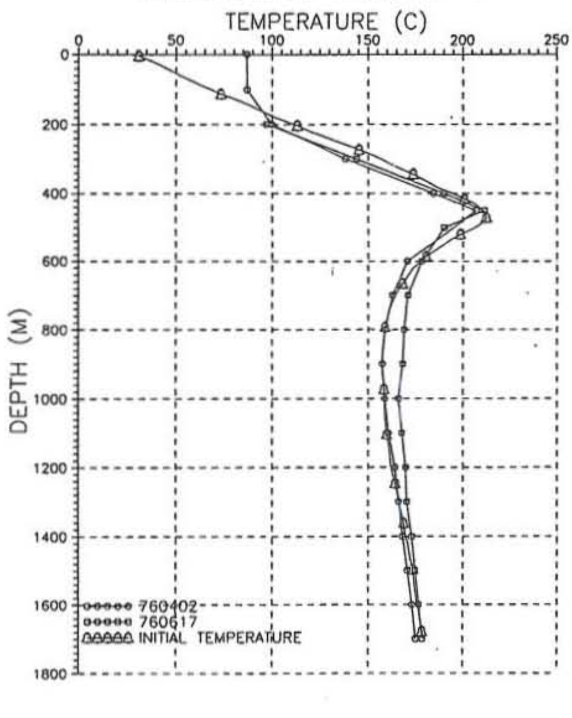
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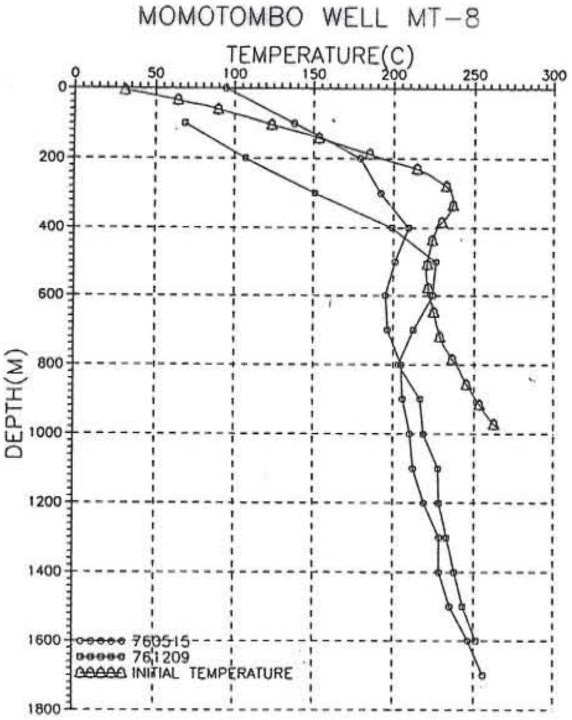
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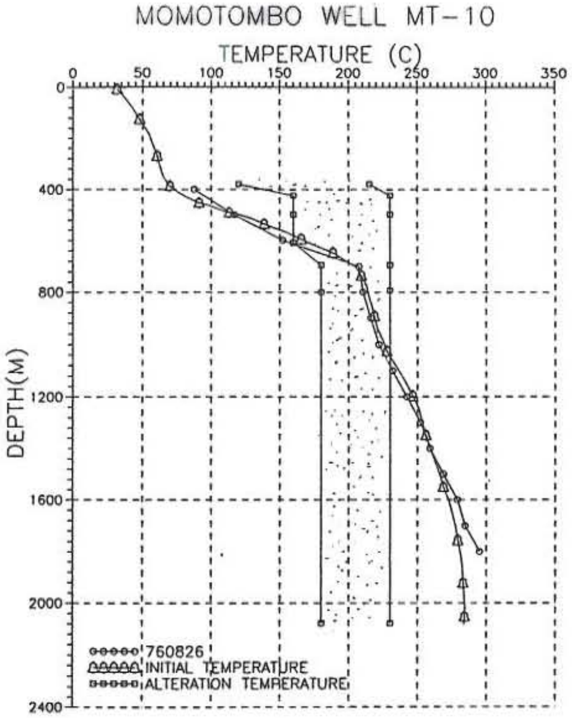
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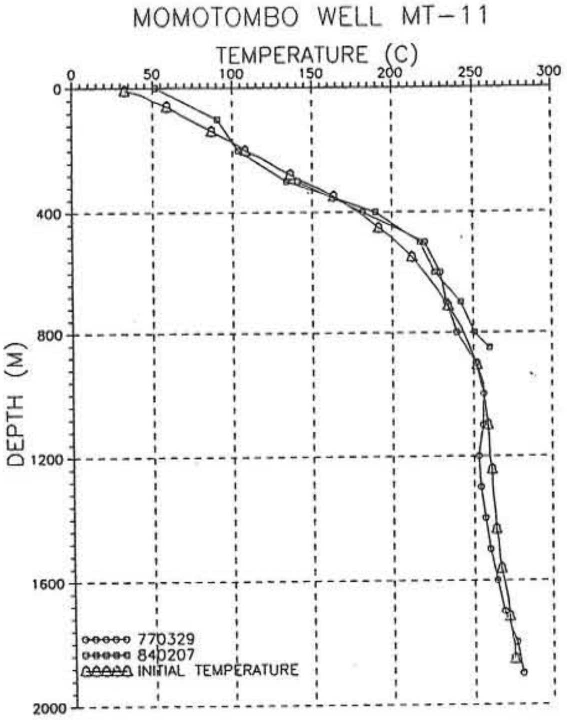
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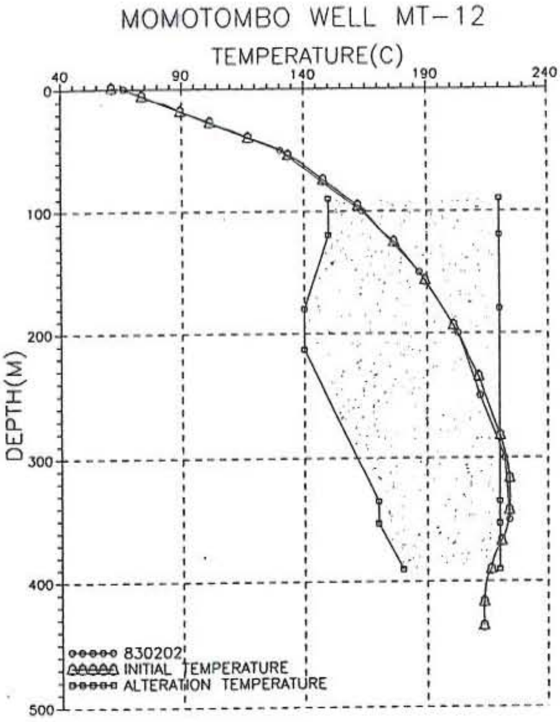
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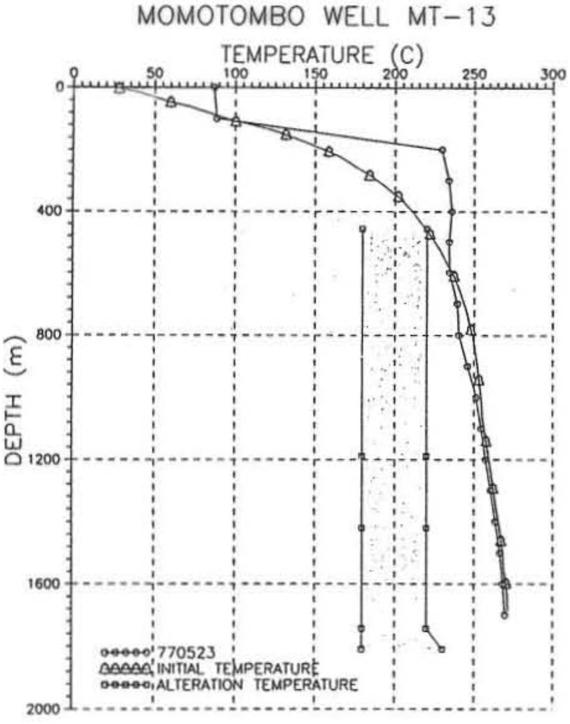
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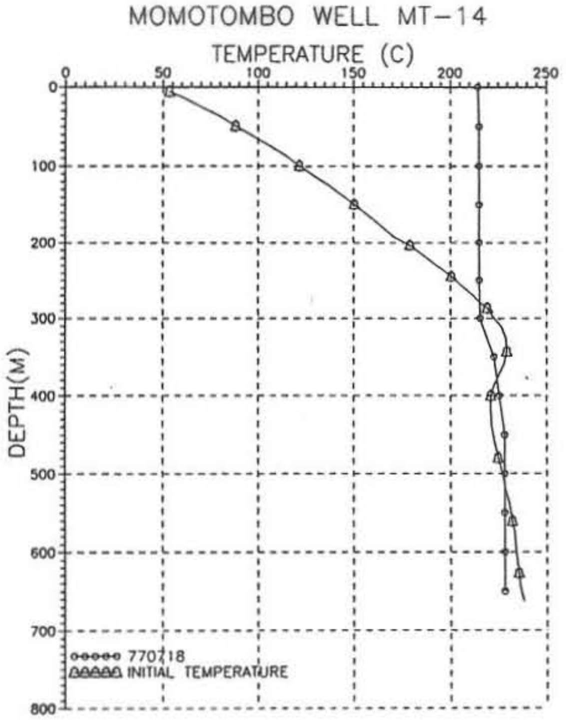
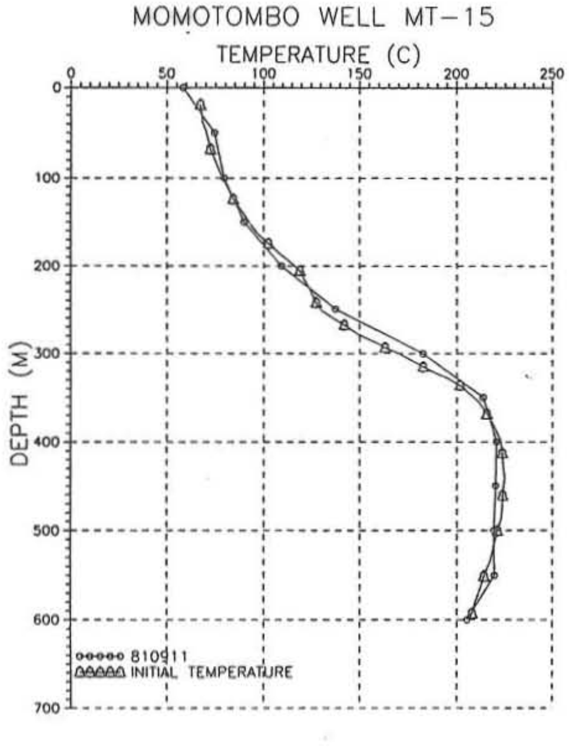
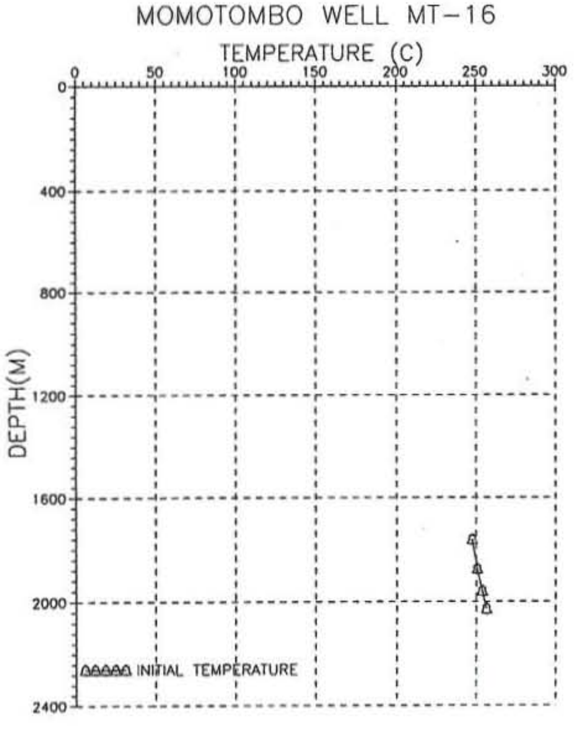
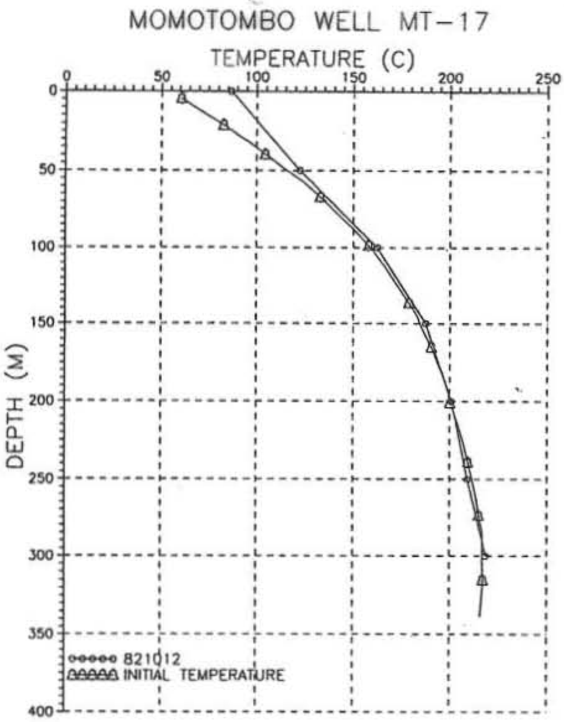
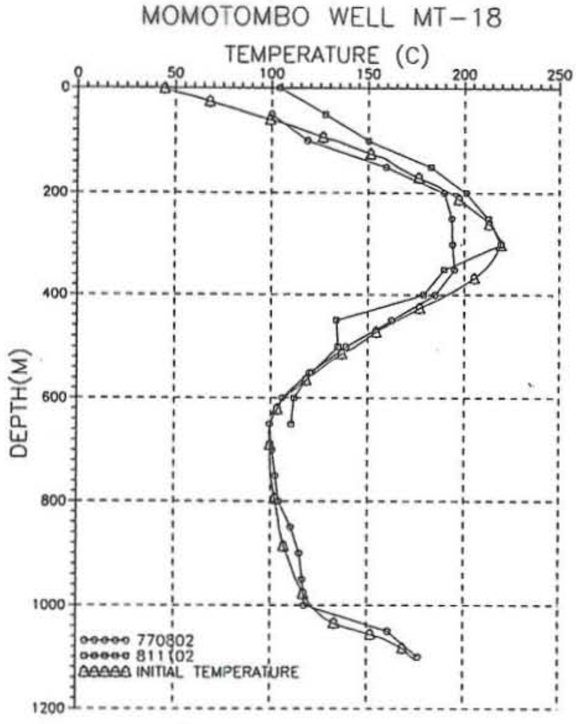
INITIAL TEMPERATURE
ALTERATION TEMPERATURE

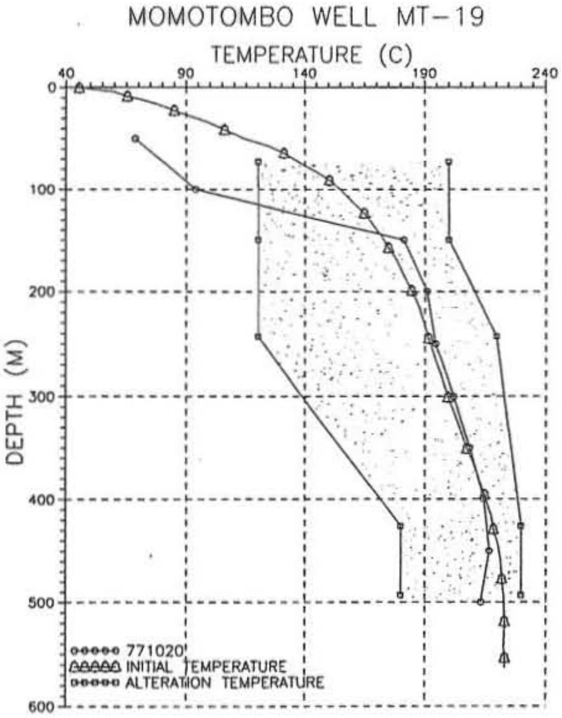

MOMOTOMBO WELL MT-14
TEMPERATURE (C)
0
50
100
150
200
250
DEPTH(M)
100
200
300
400
500
600
700
800
770718
INITIAL TEMPERATURE

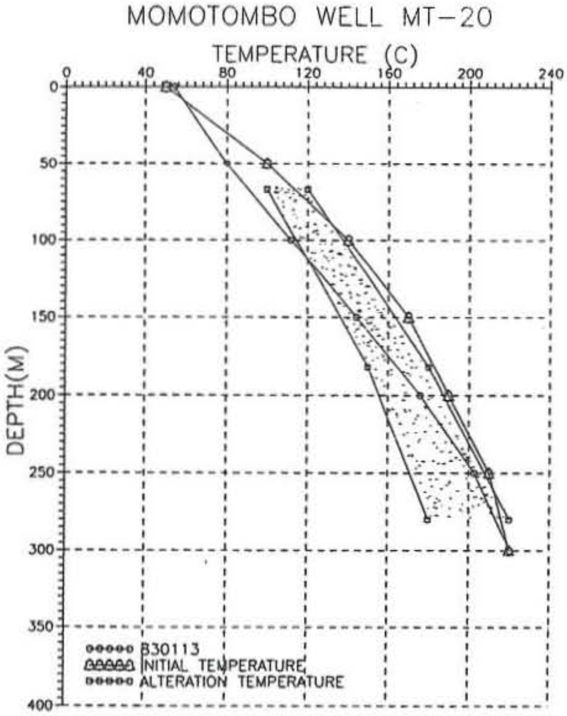

MOMOTOMBO WELL MT-15
TEMPERATURE (C)
0
50
100
150
200
250
DEPTH (M)
100
200
300
400
500
600
700
810911
INITIAL TEMPERATURE

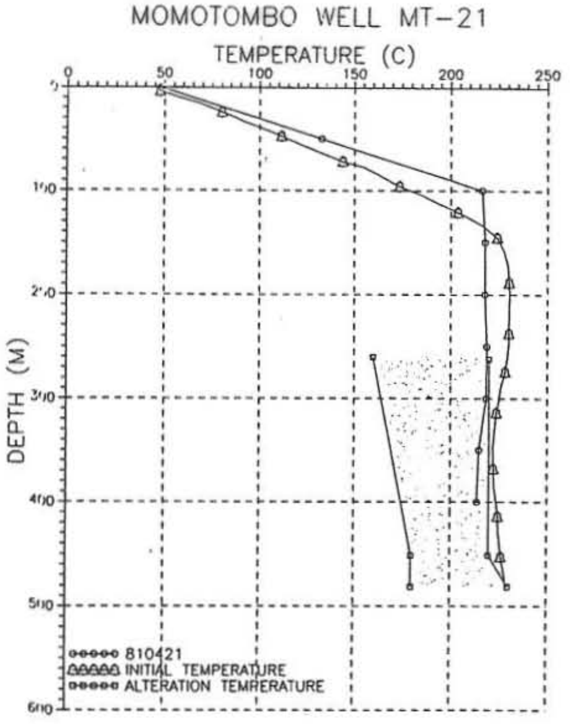

MOMOTOMBO WELL MT-16
TEMPERATURE (C)
0
50
100
150
200
250
300
DEPTH(M)
400
800
1200
1600
2000
2400
INITIAL TEMPERATURE

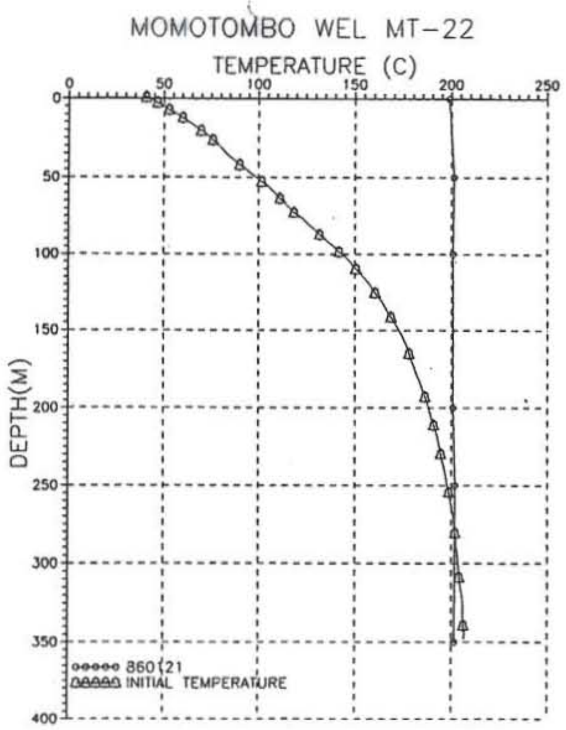

MOMOTOMBO WELL MT−17

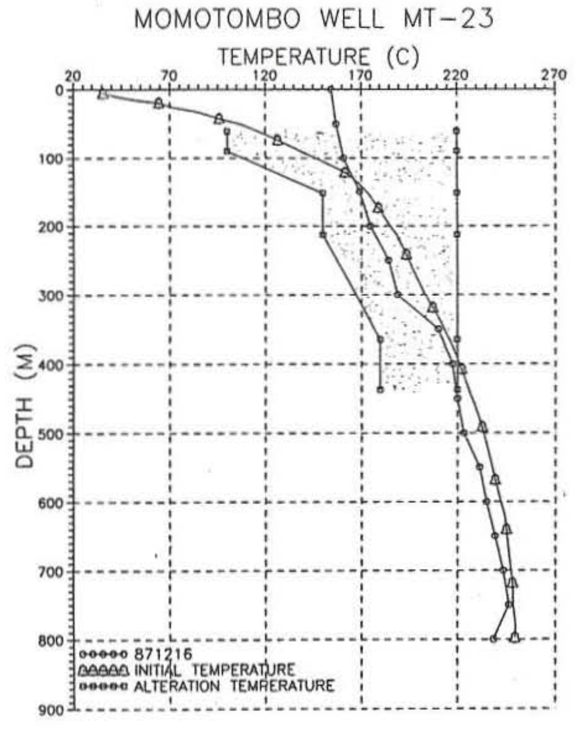

MOMOTOMBO WELL MT−18

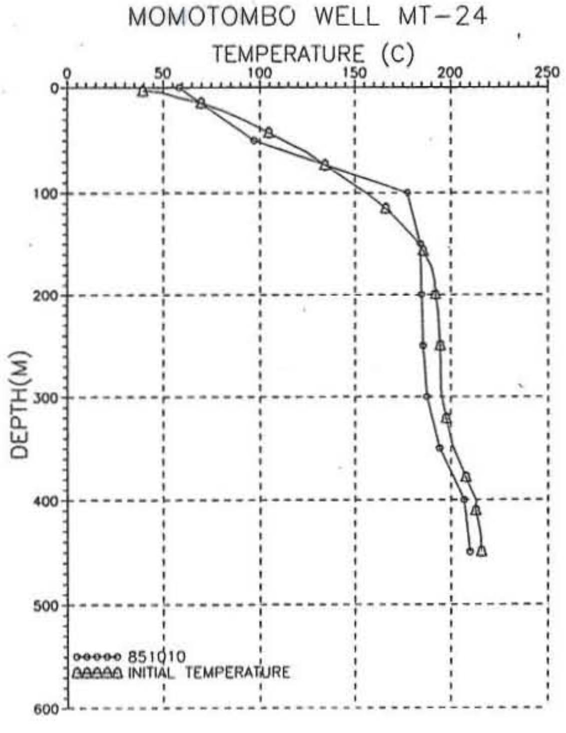

MOMOTOMBO WELL MT−19

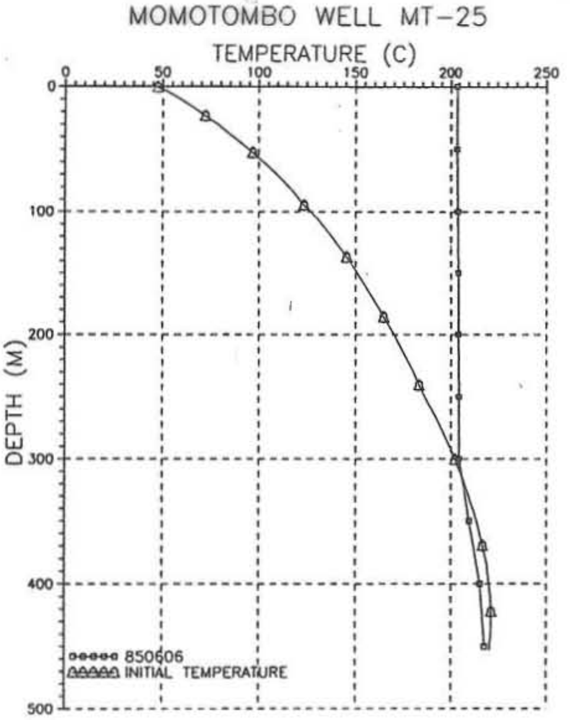

MOMOTOMBO WELL MT−20

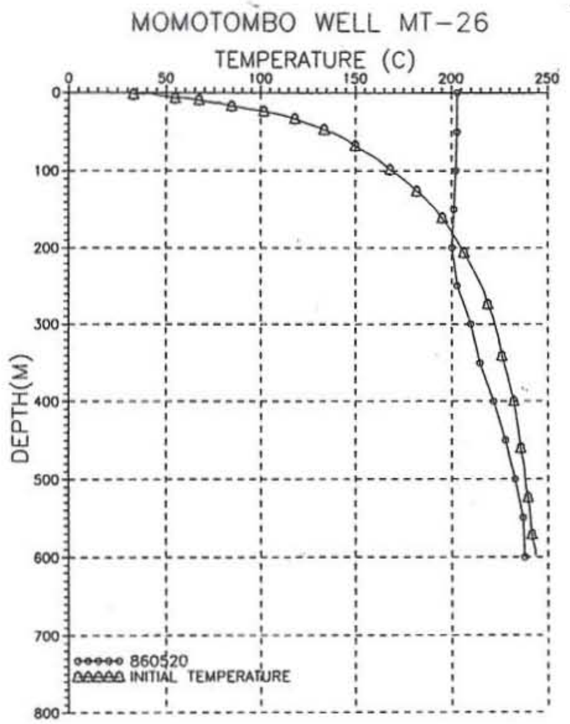

MOMOTOMBO WELL MT-21
TEMPERATURE (C)
0
50
100
150
200
250
DEPTH (M)
0
100
200
300
400
500
600
810421
INITIAL TEMPERATURE
ALTERATION TEMRERATURE

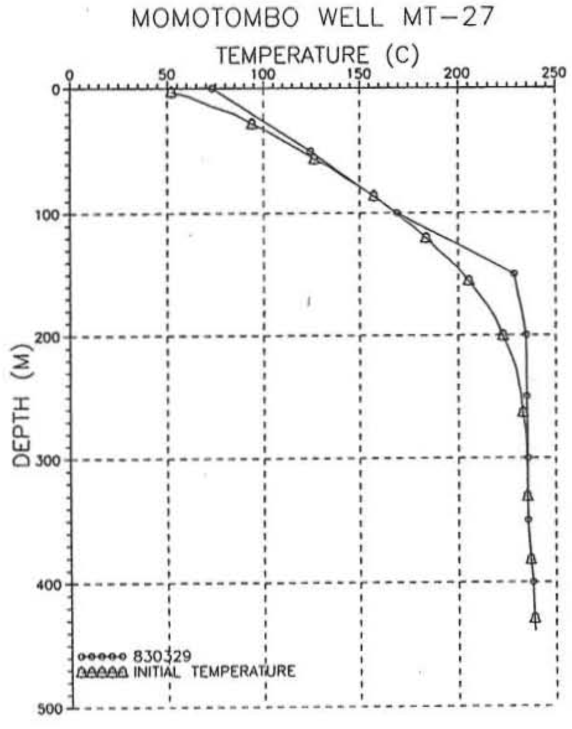

MOMOTOMBO WEL MT-22
TEMPERATURE (C)
0
50
100
150
200
250
DEPTH(M)
0
50
100
150
200
250
300
350
400
860121
INITIAL TEMPERATURE

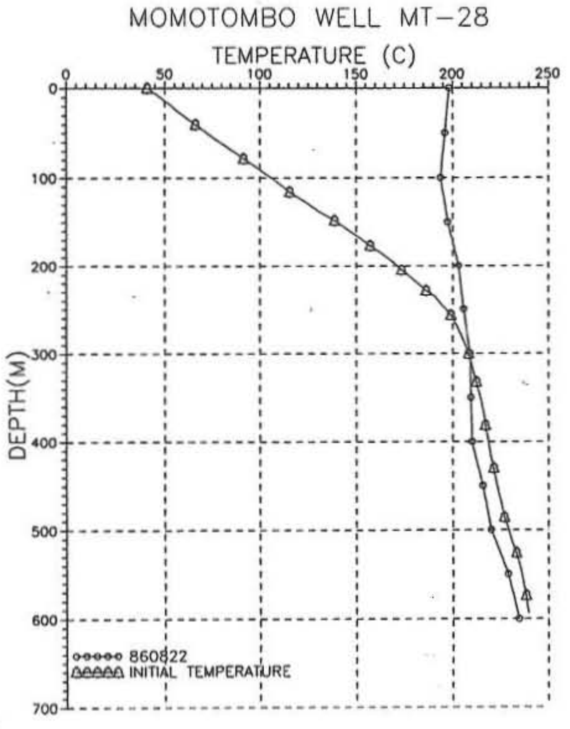

MOMOTOMBO WELL MT-23
TEMPERATURE (C)
20
70
120
170
220
270
DEPTH (M)
0
100
200
300
400
500
600
700
800
900
871216
INITIAL TEMPERATURE
ALTERATION TEMRERATURE

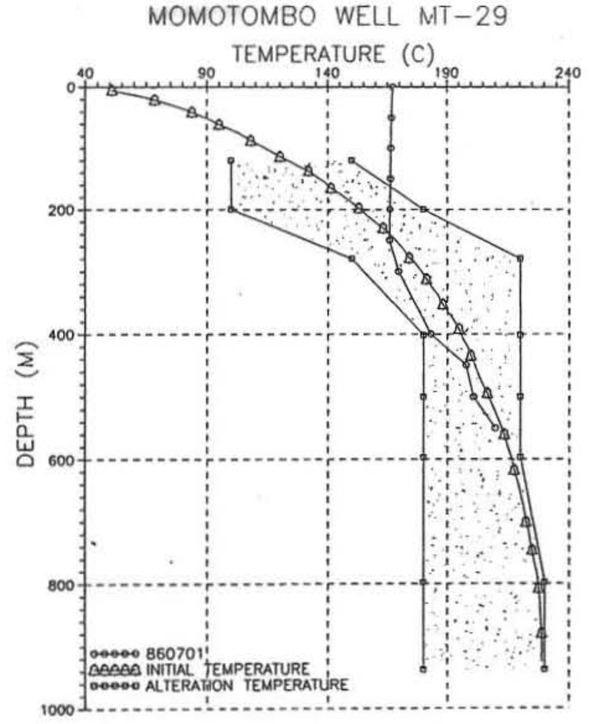

MOMOTOMBO WELL MT-24
TEMPERATURE (C)
0
50
100
150
200
250
DEPTH(M)
0
100
200
300
400
500
600
851010
INITIAL TEMPERATURE

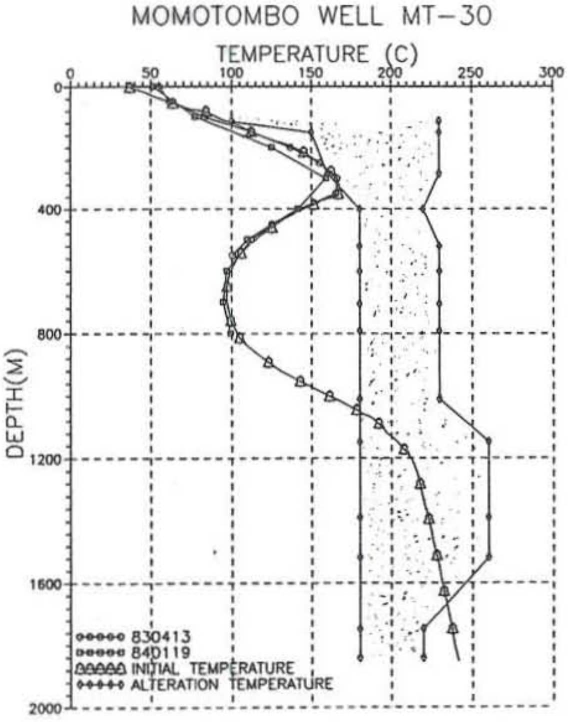

MOMOTOMBO WELL MT-25

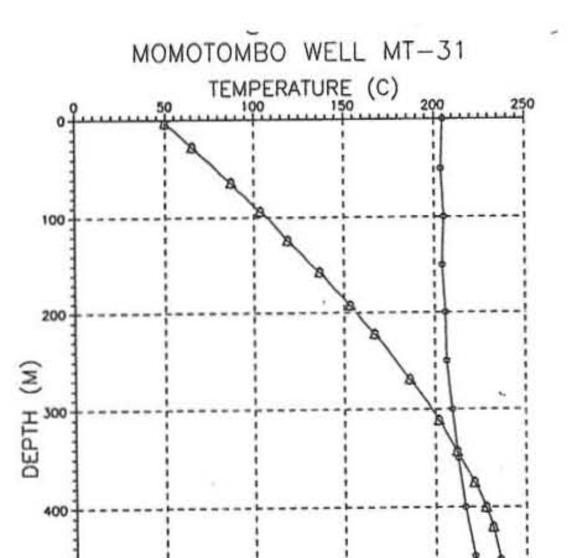

MOMOTOMBO WELL MT-26

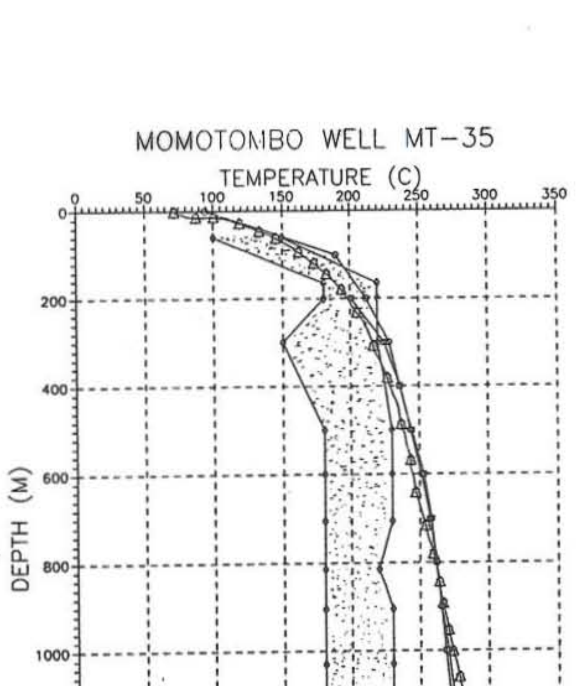

MOMOTOMBO WELL MT-27

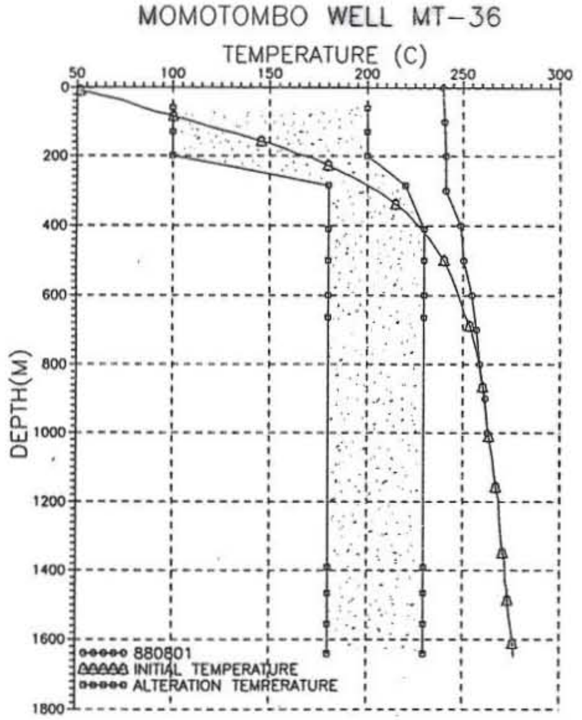

MOMOTOMBO WELL MT-28

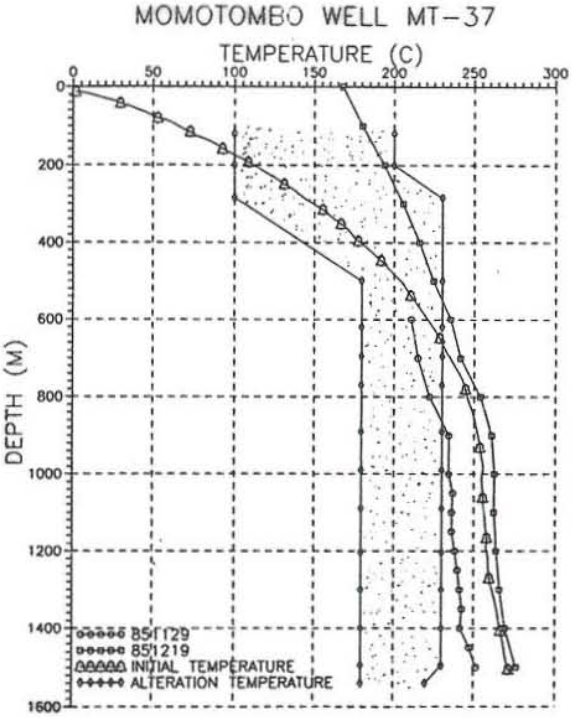

MOMOTOMBO WELL MT-29
TEMPERATURE (C)
40
90
140
190
240
DEPTH (M)
0
200
400
600
800
1000
860701
INITIAL TEMPERATURE
ALTERATION TEMPERATURE


MOMOTOMBO WELL MT-30
TEMPERATURE (C)
0
50
100
150
200
250
300
DEPTH(M)
0
400
800
1200
1600
2000
830413
840119
INITIAL TEMPERATURE
ALTERATION TEMPERATURE


MOMOTOMBO WELL MT-31
TEMPERATURE (C)
0
50
100
150
200
250
DEPTH (M)
0
100
200
300
400
500
600
800708
INITIAL TEMPERATURE


MOMOTOMBO WELL MT-35
TEMPERATURE (C)
0
50
100
150
200
250
300
350
DEPTH (M)
0
200
400
600
800
1000
1200
1400
860625
861125
INITIAL TEMPERATURE
ALTERATION TEMPERATURE


MOMOTOMBO WELL MT-36
TEMPERATURE (C)
50
100
150
200
250
300
DEPTH(M)
0
200
400
600
800
1000
1200
1400
1600
1800
880801
INITIAL TEMPERATURE
ALTERATION TEMRERATURE


MOMOTOMBO WELL MT-37
TEMPERATURE (C)
0
50
100
150
200
250
300
DEPTH (M)
0
200
400
600
800
1000
1200
1400
1600
851129
851219
INITIAL TEMPERATURE
ALTERATION TEMPERATURE