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GEOPHYSICAL EXPLORATION OF THE MOMOTOMBO GEOTHERMAL FIELD, NICARAGUA

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ABSTRACT

An integrated geophysical exploration was executed in the Momotombo geothermal resource area under ORMAT administration as part of a power output recovery program. The geophysical surveys and studies included Self-Potential, gravimetry, aeromagnetics, microearthquake monitoring, analysis and integration of an existing resistivity survey, and remote sensing study including aerial photo. The purpose of the geophysical program was to define the production drilling target areas and specific drilling targets within the ORMAT Momotombo Exploration Concession. The program resulted in the identification of several production drilling target areas. Deep drilling took place in Momotombo between 2000 and 2002; four deep wells were drilled based on the proposed drilling target areas succeeding on one of the wells. Deep production drilling targets were not reached due to drilling difficulties. The identified reservoir features by geology and geophysics are the bases for proposing an updated conceptual model of the Momotombo geothermal system.

1. INTRODUCTION

The Momotombo geothermal reservoir has been developed for more than twenty years since 1983 when the first 35 MWe unit was commissioned. The second unit was installed in 1989 by increasing steam production rate. During this period, production wells showed marked changes in flow rates, fluid chemistry and specific enthalpies of produced fluids. By 1999, when the power plant output dropped to 9 MWe an international tender was issued for the rehabilitation of the project under a 15 year Concession. Ormat won the tender and undertook to implement a power output recovery program that included an integrated geophysical exploration program to define production drilling target areas and specific drilling targets within the Ormat Momotombo Exploration Concession, with focus on the areas in and adjacent to the existing wellfield. A description of geophysical methods applied by Ormat and its results are given in this paper.

2. LOCATION OF THE MOMOTOMBO FIELD AND DEVELOPMENT HISTORY

The Momotombo geothermal field is situated about 80 km northwest of Managua city (Figure 1). The Momotombo geothermal system, covering an area of about 2 km^2, is related to the Momotombo volcano. This is one of the volcanic centres situated along the Pacific coast of Nicaragua where a chain

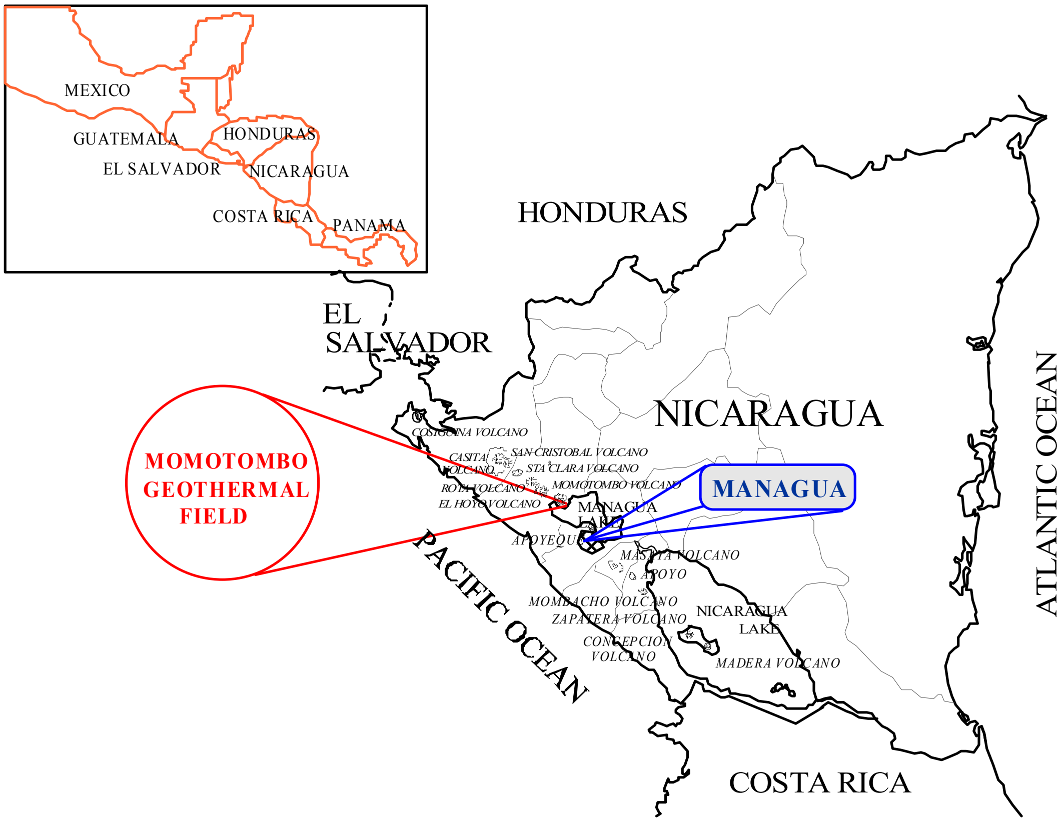

FIGURE 1: Location of the Momotombo geothermal field (after Martínez et al., 1988)

of active volcanoes is located (Figure 1). The field is situated on the northern shore of Lake Managua at the foot of the active volcano.

A total of 47 wells have been drilled as of 2002 during the four drilling stages: 1974-78, 1981-85, 1992-96 and 2000-2002. The well depths range from a few hundred meters to as deep as 2,839 m. Circulation losses were found during drilling at three different depths: 200-400 m b.s.l, 800-1400 m b.s.l and a deep zone at more than 2,000 m b.s.l., with temperatures of: 200-230°C, 250-290°C and higher than 320°C respectively.

3. GEOLOGICAL SETTING

Geologically the field is developed in the scope of the Nicaragua Depression within which the Momotombo volcanic complex is located (Figure 2). This volcanic complex consists of several small volcanic cones and a large caldera located adjacent to and northwest of the Momotombo volcano. One of the most important geological features is the Monte Galán caldera with a diameter of 4.5 km (Figure 2). The eastern edge of this caldera extends to the northwest basal slope of Momotombo, which implies that the formation of the caldera was preceded by the formation of Momotombo volcano (Goldsmith, 1975). The Monte Galán caldera has a depth of slightly more than 100 m and there are four small lakes within the caldera that were not filled with the lava flows from Momotombo. There is a small cinder cone of 525 m height, Cerro Montoso, which is located on a fissure on the northwest caldera rim of Monte Galán. The cone has discharged pyroclastics and lava flows, some of which also occupy the floor of the Monte Galán caldera. One and half km northwest of Cerro Montoso is an old, heavily eroded cinder cone, Cerro Colorado, that rises to an elevation of 225 m, displaying thermal alteration in and near the summit crater (Goldsmith, 1975).

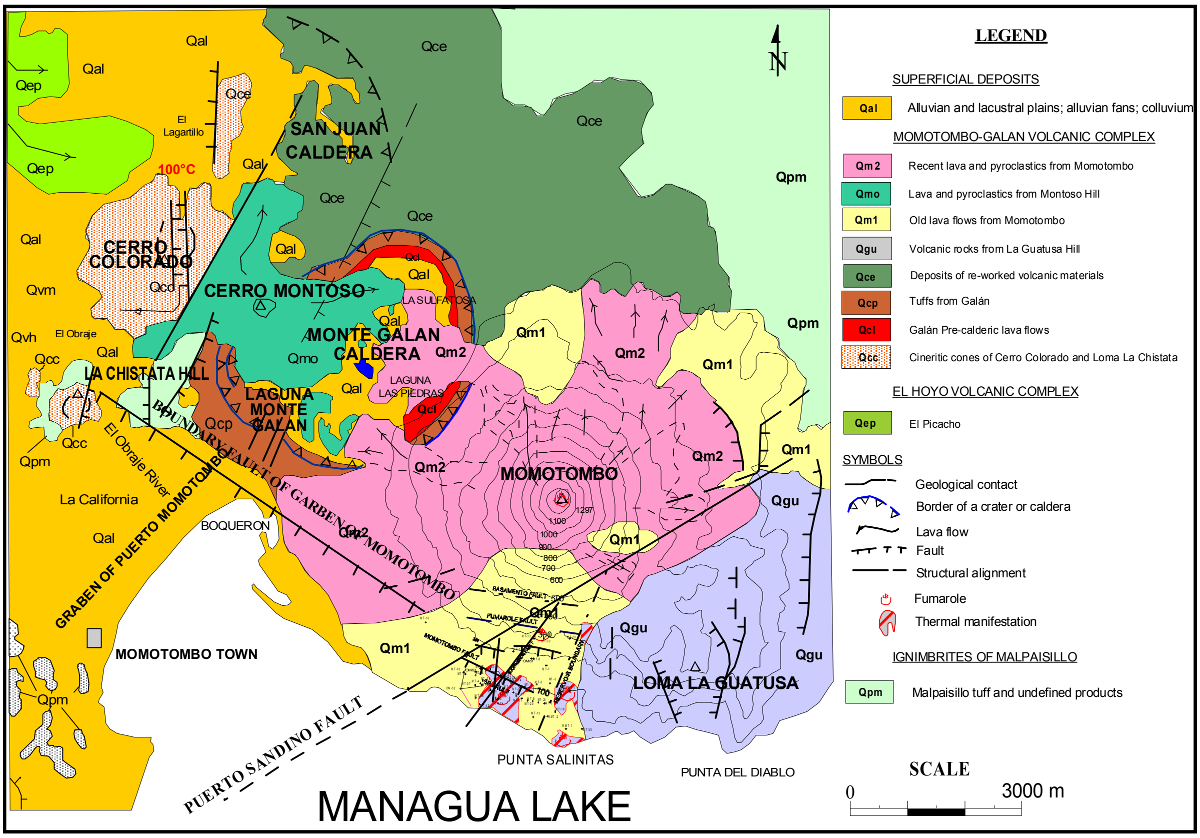

FIGURE 2: Geological map and structural frame of the Momotombo area (after Geothermex,

Three km south of Cerro Colorado is another, smaller, deeply eroded cone of 145 m height, Loma La Chistata, that rises above the plain that surrounds the Monte Galán caldera. It is cut by a fault in the south. On the south-eastern part of Momotombo and discontinuous with the slope of the volcano toward Lake Managua, is a mountain complex composed of andesitic lava flows and tuffs called Loma La Guatusa that seems to be a plateau formed by a lava flow from the Momotombo volcano. This volcanic complex is located close to the Momotombo volcano and also on the volcanic axis of the Cordillera Los Marrabios. Volcanic activity of La Guatusa occurred much earlier than that of the Momotombo volcano.

Figure 2 also shows the structural frame of the Momotombo geothermal field characterized mainly by three fault systems running NW-SE, NE-SW and N-S. The first two systems are correlated with the regional tectonics of the Nicaragua graben: the Puerto Sandino fault with a NE-SW direction and Puerto Momotombo Graben with a NW-SE direction. There are regional faults of N-S alignments. A set of these faults allows the circulation of fluids in a hydrothermal system. As the most productive shallow wells are located generally in a zone corresponding to structural crossings, the recharge zone for the shallow reservoir possibly presents in a fractured zone formed in the intersection of faults of these three systems. Figure 3 shows the location of the main faults within the well field. Fluid seems to be transported from depth through the western most fault of the NE-SW direction. Then it changes direction at a shallow depth after reaching the Bjornsson fault, and then fluid flows in a horizontal layer at a shallow depth after reaching Momotombo fault and the shallow reservoir located generally in a zone corresponding to structural crossings, the recharge zone for the shallow reservoir possibly presents in a fractured zone formed in the intersection of the faults of these three systems.

On the basis of the petrographic and macroscopic analysis of drilling cuttings and cores, the lithology of the Momotombo geothermal field has been divided into six units that consist of andesite and andesite-basaltic volcanic products, volcano-clastic deposits, different kinds of tuffs, volcano-sedimentary and sedimentary deposits, and some sub-intrusive bodies and dikes (Combredet et al., 1987). The geological interpretation of these units suggests that a long period of volcanic activity took

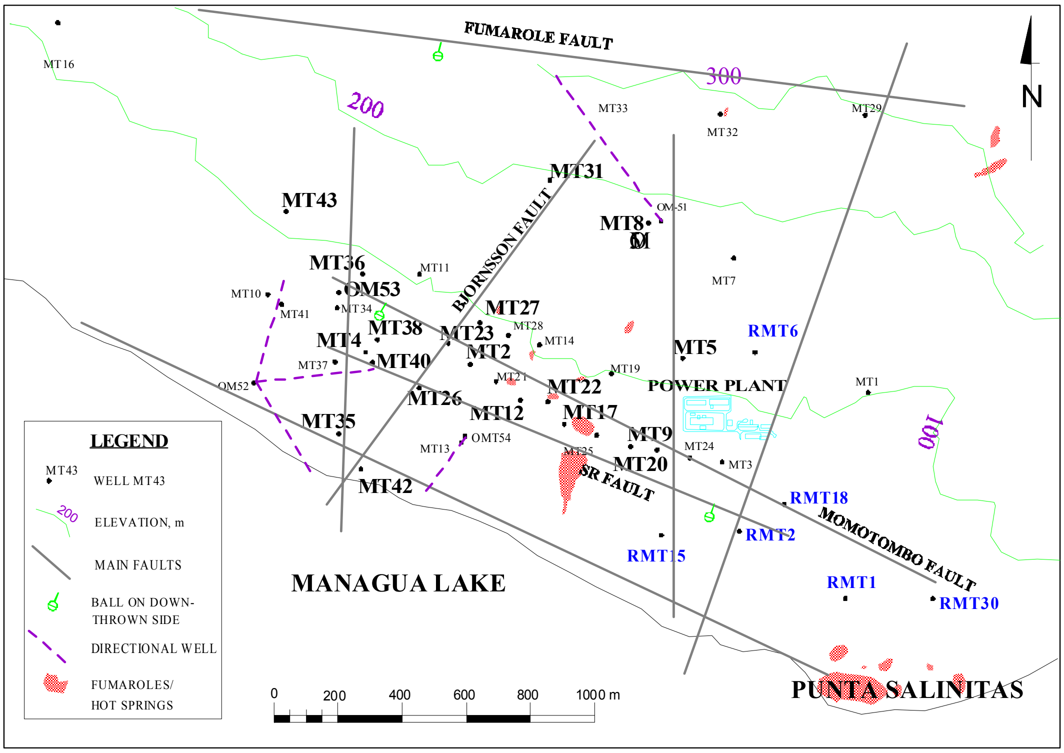

FIGURE 3: Location map of wells and main faults in Momotombo

place in the area. Such activity generated a 1,700 m thickness of different volcanic and volcano-sedimentary products, and the presence of sedimentary rocks combined with volcanic rocks in the deeper zones. All these units had been formed during early Miocene to the Quaternary age.

Figure 4 shows a petrological correlation by Combredet et al. (1987) in four wells located in the western part of the field. It also denotes the depth of the lithological contact between three of the six

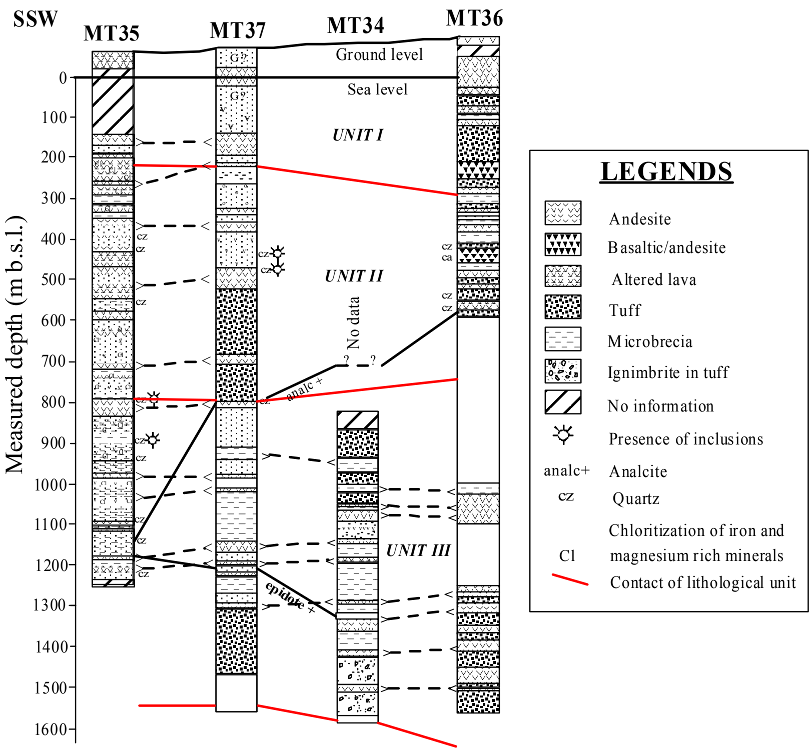

FIGURE 4: Petrological correlations between wells in the western part of the well field
(after Combredet et al., 1987)

lithological units in Momotombo. They also reported the depth of appearance for minerals such as epidote and quartz. The figure presents that epidote, which is an indicator of high temperature (>240°C) fluid circulation, is found at relatively shallow depths in well MT35 inferring a presence of a high temperature zone in this area.

3. OVERVIEW OF GEOPHYSICAL PROSPECTING

Geophysical explorations were carried out in Momotombo in seven different periods between 1970 and 2000. The most recent studies (DAL SpA, 1995 and TRANSPACIFIC, 2000) are closely related to defining new drilling sites for production wells as part of the power output recovery plan implemented by ORMAT and identified the main hydro-geological features of the Momotombo geothermal system. Table 1 presents a summary of the geophysical studies carried out so far.

TABLE 1: Geophysical surveys conducted in the Momotombo field (after Geothermex, 2001)

Company	Year	Method	Depth research (m)	Max. distance ab or dipoles (m)	Area (km^2)	Profiles		Number of surveys	Number of measurem. sites
						No.	Total length (km)		
Texas Instruments	1970	Gravimetry Magnetometry SEV Schlumb Dipole map Electro-Mag Audiomagnetoteluric	268 ? 1700 ?	1000 <3000	8	1 1 1	6 6 3	8 3 16	? ? 86
United Nations	1974	SEV Schlumb Schlumberge Profile Dipole Maping		2000		6 ?		?	35 ? ?
Electro-Consult	1974- 75	SEV Schlumberger Gravimetry	1000	3000	5			20	
Phoenix Geophysics	1977	Dipole-dipole Recon Dipole-dipole detail	1450	3750 3750	300 5	14 6	200 48	225 44	
OLADE	1982	Regional Gravimetry Regional Magnetom			1500				
DAL	1995	Frequency soundings			10	12			
ORMAT/ TRANSPACIFIC	2000	Self-Potential Gravimetry Aeromagnetics Microearthquake Mo		50 100			44.3 370		886 525 13

During the 1970's and early 1980's the geophysical surveys were carried out as part of the pre-feasibility study for the development of the geothermal field. Among others, ELC (1976) and OLADE (1981) conducted gravity measurements that revealed the characteristic structure of the geothermal system. For example, these studies confirmed the existence of a high regional Bouguer anomaly in a NW-SE direction, which coincides approximately with the active volcanic axis from the Momotombo geothermal field up to the town of Malpaisillo (Figure 5).

Figure 5 shows a Bouguer gravity anomaly map by Cordon (1980) and then modified by DAL SpA, (1995). This gravity survey was conducted at 200 stations over an area of approximately 300 km^2. The density values for the shallow layer and the underlying "Basement" are 2.3 g/cm^3 and 2.6 – 2.8 g/cm^3 respectively.

There are high anomalies in correspondence to the Galán and San Juan caldera (Figure 5); another anomaly is located to the southeast of the Momotombo volcano where the geothermal field is located. However, gravity survey in detail suggests that there are plateau like contours followed by descending gravity in the north-western part of the field with gravity values between 1.914 and 1.905 g/cm3 (Figure 6).

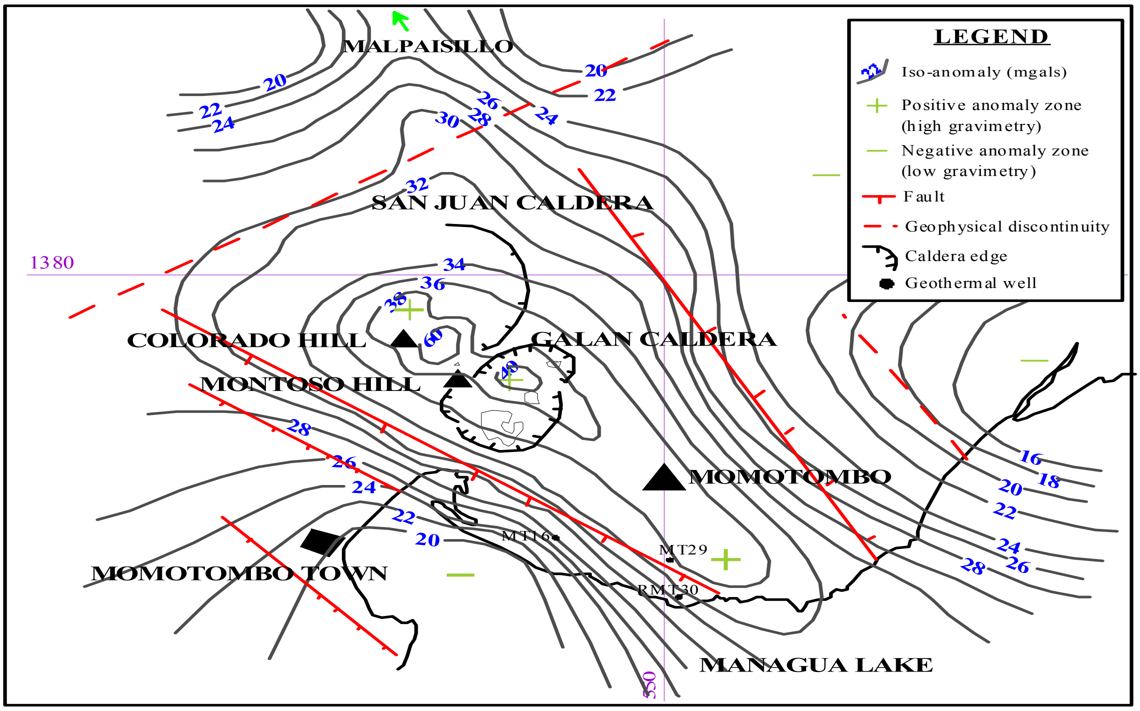

FIGURE 5: Bouguer gravity anomaly map after Cordon (1980) and DAL SpA (1995)

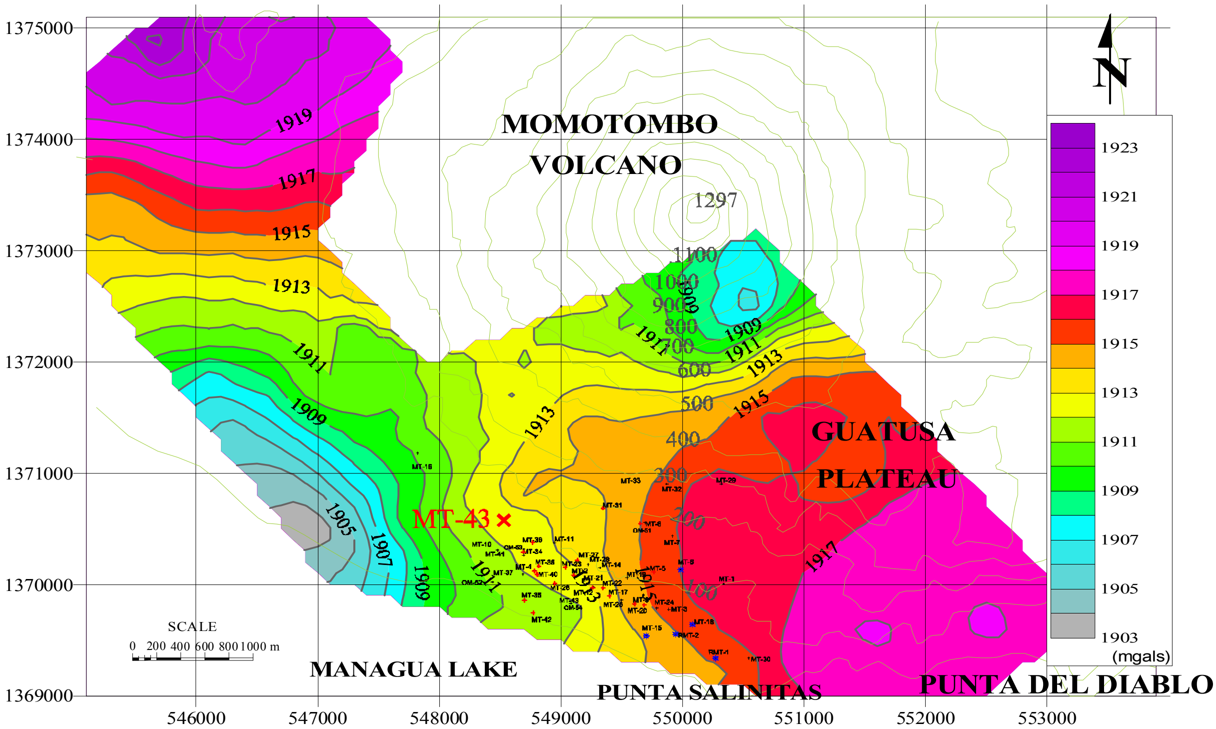

FIGURE 6: Bouguer gravity map (after TRANSPACIFIC, 2000)

The high gravity in the eastern part of the well field near Punta del Diablo (Figure 6) may represent a body of high resistivity zone related with hydrothermal alteration activity (OLADE, 1981); the increase in gravity is associated with a more dense formation due to intense silicification. Another interpretation to this high local gravity is a presence of a basement with a thick sequence of lava (OLADE, 1981). The descending gravity to the north-western area may correspond to the upflow zone where a series of NW-SE faults have been described by geological studies (DAL SpA, 1995).

4.1 ORMAT geophysical programme

An integrated geophysical exploration program was executed in the Momotombo geothermal resource area that included four other different surveys such as self-potential, gravimetry, aeromagnetic and micro-earthquake monitoring. The purpose of the program was to define production drilling target areas and specific drilling targets within the Ormat Momotombo Exploration Concession, with focus on the areas in and adjacent to the existing wellfield. Figure 7 shows the resistivity contours at depths

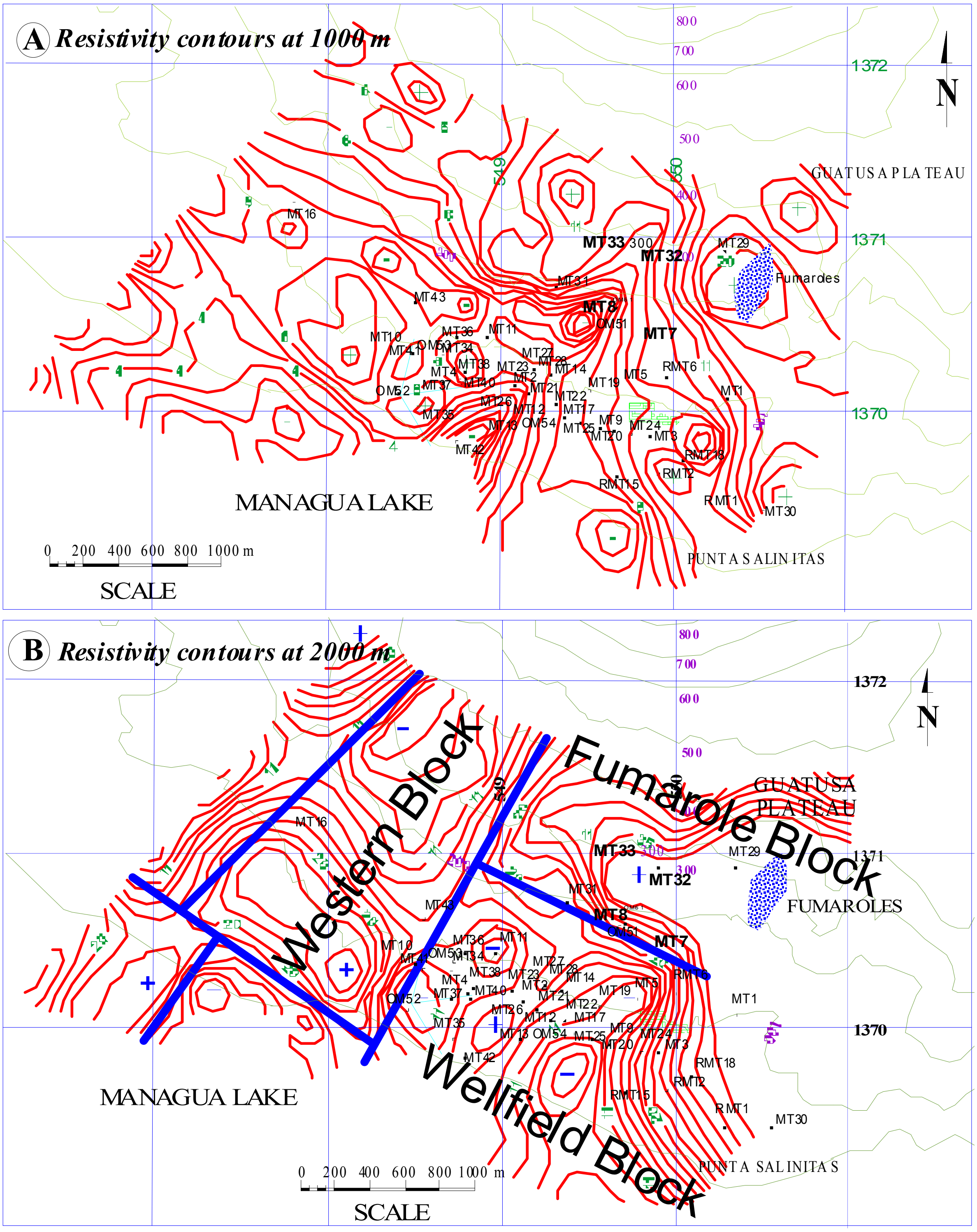

FIGURE 7: Resistivity contours at 1,000 and 2,000 m depth
(after DAL SpA and TRANSPACIFIC, 2000)

of 1,000 m (A) and 2,000 m (B) from the surveys carried out in 1995 (DAL SpA, 1995). As shown in Figure 7, the field has been divided into three areas depending on resistivity values. They are the Wellfield, Western, and Fumarole blocks. The Wellfield block, where the wells are located, is characterized by generally low resistivity values. The Fumarole block is located to the north of the Wellfield block and is characterized by higher resistivity values, and there is a large fumarolic area present. Another high resistivity zone is located to the west of the Wellfield block. This area is represented by the Western block in Figure 7b.

The results show that the Fumarole block is characterized by high resistivity. Figure 7b shows that the line dividing the Fumarole block with the Wellfield block corresponds with a resistivity boundary where production wells are located (Figure 7a (MT7, 8, 32 and 33)). The resistivity boundary is also evident at 1,000 m depth. This resistivity pattern at depth suggests a presence of possible fractures along the various resistivity boundaries that are defined by discontinuities of the resistivity contours.

The program identified additional exploration targets (Figure 8), which are located outside the area capable of supplying the existing power plant but within the Ormat Momotombo Exploration Concession. These target areas currently contain no drill holes and nothing is known about the deep temperature regime.

Four deep wells were drilled by ORMAT between 2001 and 2002 following the geophysical study results. A total length of 7,097 m was drilled from which well OM53 resulted in being commercially productive and has become the best steam producer of the field. Another well, OM52, is now used as a brine injector.

Geophysical studies suggest deep drilling targets (deeper than 2,500 m) for production wells. None of the four drilled wells by ORMAT was able to reach more than 2,100 m, except OM52 (> 2,800 m).

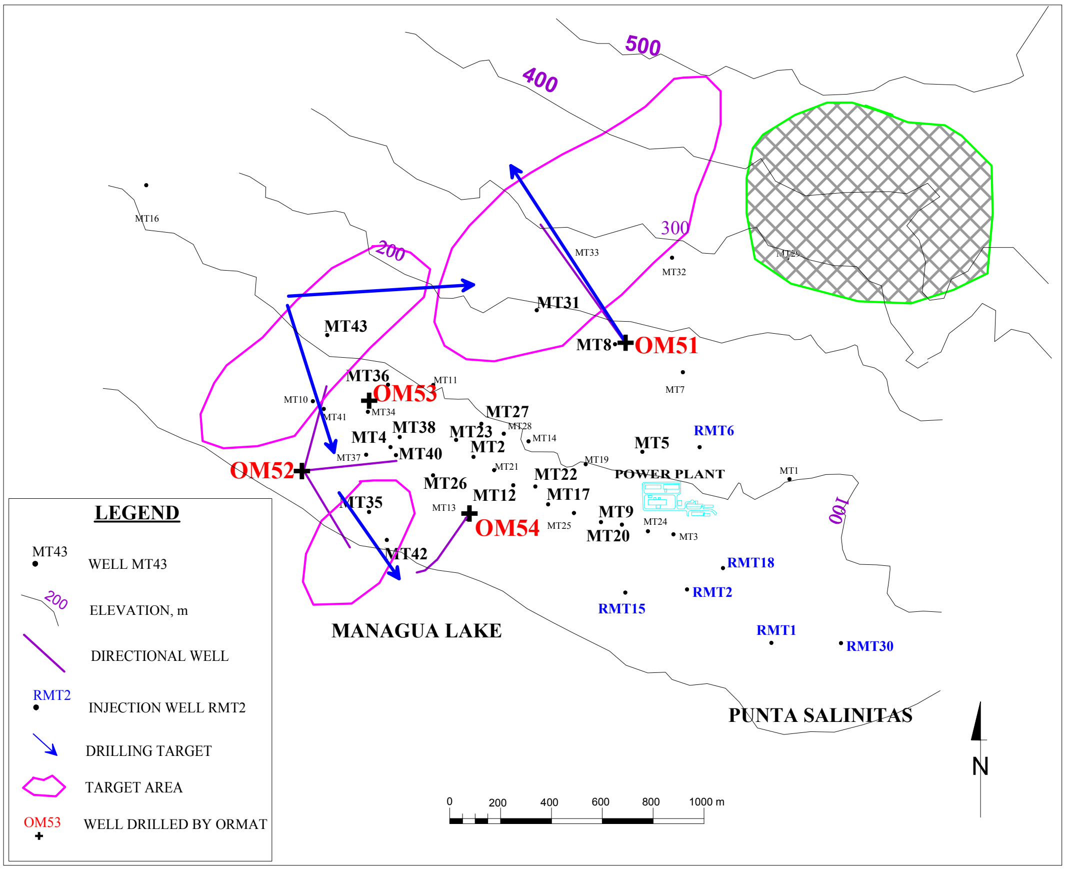

FIGURE 8: Drilling targets for deep drilling in Momotombo

Such deep targets are still considered as promising for steam production in order to increase the current power output up to the current installed capacity of 77 MWe. ORMAT is willing to invest in new studies and drillings only if the concession term is extended beyond the remaining six years.

5. CONCLUSIONS

Characteristics of subsurface and physical phenomena were revealed by reviewing and interpreting the studies carried out since late 1960's in the Momotombo area. Thus, features of the geothermal system in Momotombo can be summarized as follows.

1) Three main fault systems control fluid flow in the reservoir.
2) A low resistivity anomaly in the eastern part of Momotombo probably plays a role as a reservoir boundary of no flow to the east.
3) On the basis of the features suggested by geology and geophysics a conceptual model can be proposed for the Momotombo geothermal system.
4) Geophysical studies suggest deep drilling targets (deeper than 2,500 m) for production wells, from the four drilled wells by ORMAT, non of them was able to reach more than 2,100 m, except OM52 (> 2,800 m).

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