GEOLOGIC AND RESERVOIR MODEL OF THE MAIBARARA GEOTHERMAL FIELD

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SUMMARY - Hydrothermal alteration and fluid inclusion data were used to help develop the geologic and reservoir conceptual model of the Maibarara field. This conceptual model forms the basis for an on-going reservoir simulation study. Within the 2.5 km^2 proven production area, there is a good correlation between both fluid inclusion temperature and alteration mineralogy with measured wellbore temperatures, while outside this area the correlation is poor. South of the central benign chloride reservoir, acidic fluids occur along discrete stratigraphic zones, as demonstrated by the presence of pyrophyllite. On the northern margin of the field. considerable cooling has occurred due to incursion of cooler shallow fluids. A comparison of the past (evidenced by fluid inclusions and alteration mineralogy) with the present (measured) temperatures shows that the reservoir has contracted, and the margins have cooled by at least 60°C over time. The presence of marginal cooler and acidic fluids limits the potential development size of the Maibarara resource. The installation of an 11 MWe power plant is under considention by the National Power Corporation.

1. INTRODUCTION

The Maibarara geothermal field is the second geothermal resource discovered in the Makiling-Banahaw (Mak-Ban) contract area. Laguna, Philippines. It is currently being considered for development by Philippine Geothermal. Inc. (PGI) in partnership with the National Power Corporation (NPC). Maibarara is located at the western foot of Mt. Makiling stratovolcano. about 3 km NW of Bulalo geothermal field. Bulalo field has an installed capacity of 346 MWe, and currently supplies about 14% of the electricity of the Luzon grid (Sussman *et al.*. 1993). Exploration at Maibarara began in 1974. and 12 wells have been drilled to date.

Hydrothermal alteration in geothermal systems can indicate the temperature. permeability. pressure. and fluid composition during mined formation (Reyes. 1990). Comparing hydrothermal alteration and formation temperatures from fluid inclusions trapped in hydrothermal minerals can yield important information on temporal changes in a geothermal reservoir. Understanding the evolutionary state of a geothermal system (i.e., immature. mature, receding) can guide reservoir modelling and field development strategies.

This paper presents the results of a hydrothermal alteration study conducted for the Maibarara geothermal field to help develop the geologic and reservoir conceptual model. This conceptual model forms the basis for an on-going numerical reservoir simulation study.

2. GEOLOGY

2.1 - Geologic Setting

Maibarara and Bulalo geothermal fields occur near the intersection of the northern Luzon volcanic arc (Figure 1, inset) and the Macolod comdor, a 40 km wide NE-trending structural belt which contains a large caldera, two stratovolcanoes, and a maar field (Wolfe and Self, 1983). This segment of the volcanic arc consists of Pliocene to Recent volcanic centers associated with the eastward subduction of the South China Sea Plate along the Manila trench (Oles, 1991). The volcanic rocks are mainly

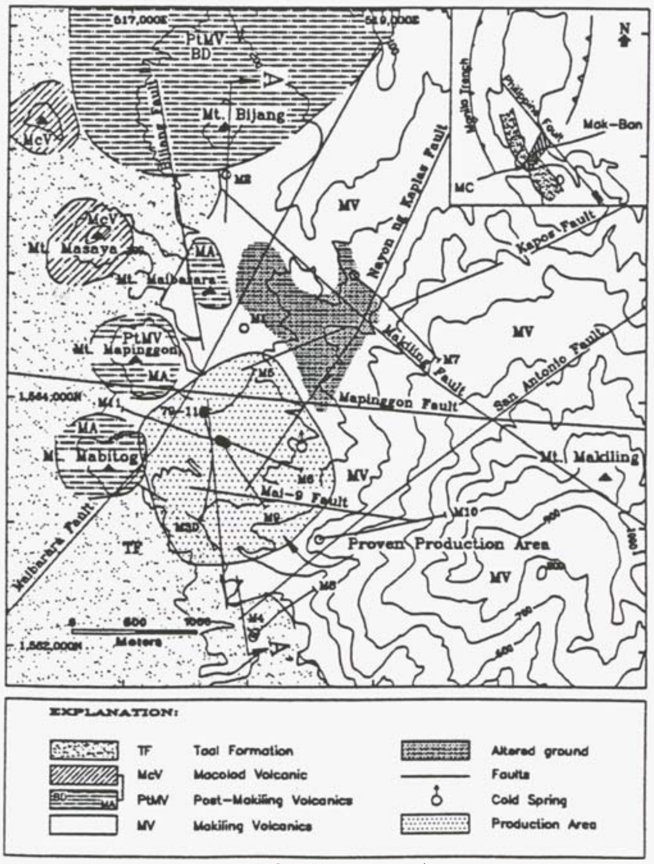

figure 1: Geologic map of the Maibarara Area. Inset shows tectonic setting of Luzon. Stippled areas in inset are the Bataan and Mindoro arc; hatched area is the Macolod Corridor (UC).

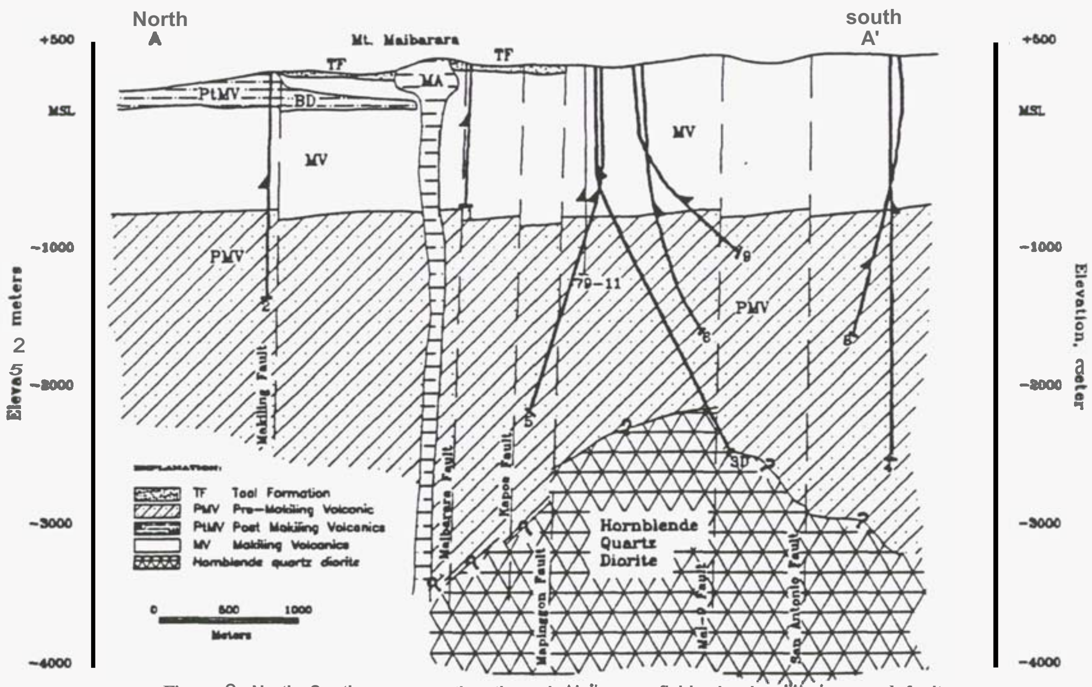

Figure 2 North–South cross–section through Maibarara field, showing lithology and faults.

andesitic, but range in composition from dacite to basalt (Defant. *et* al.. 1990). Maibarara is situated on the northwestern flank of Mt. Makiling, an extinct andesite stratovolcano within the Macolod Corridor.

The surface geology of the western part of Mt. Makiling and the outline of the Maibarara geothermal field are shown in Figure 1. Parasitic lava domes of intermediate to silicic composition (Post-Makiling Volcanics, PtMV) and two basaltic cinder cones (Macolod Volcanics, McV) occur on the western flanks of the volcano. Recent tuffs derived from the collapse of Taal volcano. 20 km southwest of Mt. Makiling, cover the lowlands to the west. Radiometric dates on lavas from Mt. Makiling and the parasitic domes range from 2.7 to 0.25 Ma (Clemente and Abrigo. 1993). suggesting nearly continuous volcanic activity from Late Pliocene to the Quaternary. Maibarara field is adjacent to three andesite lava domes (Mts. Maibarara, Mapinggon and Mabitog) and a dacite dome (Mt. Bijang). Potassium-argon dates on the Bijiang dacite (BD) and the Mabitog andesite (MA) domes yield ages of 1.16 m.y. and 1.08 m.y., respectively.

2.2 - Stratigraphy

The subsurface geology of the Maibarara area (Figure 2) has been interpreted from well cuttings and drill cores. The upper part of the geologic section consists of 40 to 60m of Taal Formation (TF) ash flow tuff. The TF is underlain by a thick sequence of andesitic lavas and pyroclastics (MV) from successive eruptions of Mt. Makiling. Beneath this formation are the Piio-Quaternary Pre-Makiling Volcanics (PMV), which consist of thick dominantly andesite lava flows with minor intercalations of tuff and andesite breccia. This sequence of generally massive and dense rocks hosts the Maibarara reservoir. A hornblende-quartz diorite pluton intrudes the PMV. The relationship of this intrusion to the geothermal system has not been determined.

2.3 - Structures

The Maibarara area is dominated by two sets of structures, one trending NE and the other E-W. Some of these faults act both as conduits for reservoir and peripheral fluids, and others act as permeability boundaries. Figure 1 shows the primary mapped structures in Maibarara.

The dominant NE-trending faults parallel the structural orientation of the Macolod Corridor. These faults generally exhibit normal displacement and form a series of horsts and grabens in the reservoir. The productive reservoir is located between the Maibarara and San Antonio faults (Figure 1). The southern segment of the Nayon ng Kaplas fault bisects the production area. and is believed to be the main conduit for upflowing geothermal fluids. The Maibarara fault appears to be the western boundary of the Maibarara geothermal reservoir (Abrigo, *et al.*, 1994). No circulation losses were experienced during drilling when this fault was encountered, and lower temperatures and tight rocks were observed between the fault and the bottom of the well. The Maibarara fault shows reverse movement with a relative vertical displacement of about 300m as determined from the offset of the diorite pluton (Figure 2). Another NE-trending structure. the Kapos fault, defines the northern limit of known production. The northern segment of the Kapos fault and the Nayon ng Kaplas fault (Figure 1) appear to be pathways for cooler fluids influxing towards the northern margin of the production area. Likewise, cooler dilute fluids skirt the southeastern margin of the Maibarara field through the San Antonio fault.

A second fault set. represented by the Mapinggon and Mai-9 faults. strikes E-W (Figure 1). The Mapinggon fault appears to control the orientation of the volcanoes in the Macolod Corridor east of Mt. Makiling (Oles *et al.*, 1991). The Mai-9 fault parallels the Mapinggon fault and was encountered by Mai-9. Within the reservoir, both structures are productive targets; outside the proven reservoir, the Mai-9 fault is a conduit for cooler fluids migrating into the southeastern margin of the field.

A third fault group is oriented N-S and bisects the reservoir. This set is represented by the Bijiang fault (Figure 1). Fractures related to this fault are good sources of production.

2.4 Thermal Manifestations

The only surface feature associated with hydrothermal activity at Maibarara is an 0.8 km² heart-shaped area of altered ground. It is found near the intersection of the Nayon ng Kaplas, Kapos, and Makiling faults (Figure 1). The altered ground is probably formed by steam-heated groundwater related to northeastern shallow outflow from the Maibarara reservoir (Abrigo, *et al.*, 1994). Thermal activity is limited to scattered small patches of warm to steaming ground.

3. GEOPHYSICS

Maibarara was initially explored with a dipole-dipole survey, and later with 60-150m temperature gradient wells, and Bouguer gravity and magnetotelluric (MT) resistivity surveys. The productive geothermal reservoir was initially defined by the dipole-dipole low resistivity anomaly (Figure 3). The elongated N-S trending dipole-dipole and MT resistivity anomalies coincide north of the reservoir, and appear to map out a clay cap associated with the outflow tongue penetrated by exploration wells Mai-1 and -2 (Pedersen and Fernandez, 1985). MT low resistivity and a negative gravity anomaly indicate an extension of the clay cap to the south, and further define the reservoir.

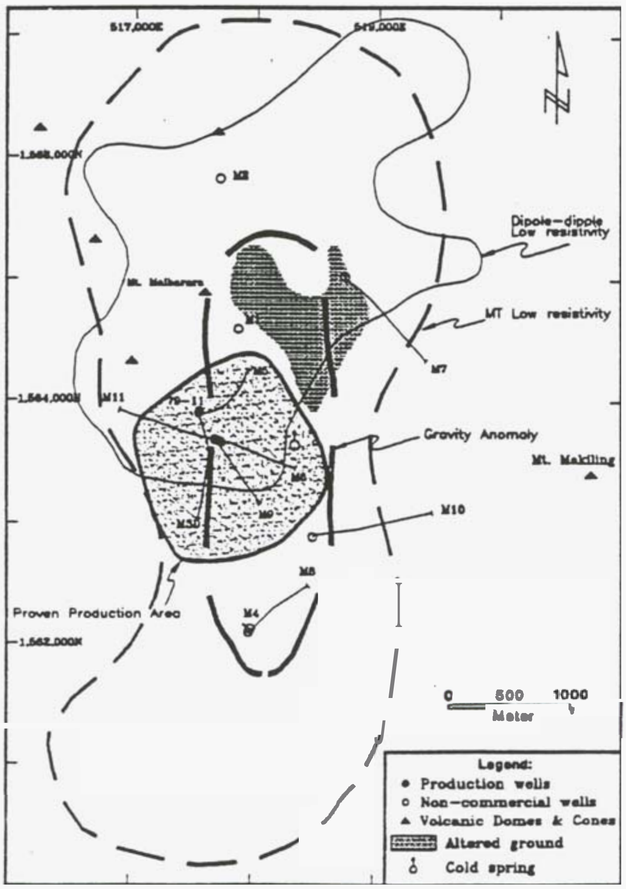

Figure 3. Plan view of the Maibarara field showing the dipole-dipole and MT resistivity, and gravity anomaly relative to the proven resource.

4. DRILLING RESULTS

A total of 11 conventional sized wells (9-5/8" production casing) and a slim hole were drilled at Maibarara between 1977 and 1983 (Figure 3). The first two wells (Mai-1 and -2) were drilled within the dipole-dipole low resistivity anomaly and encountered temperature reversals at depth. The third well, Mai 79-11, discovered the high temperature reservoir. Succeeding wells delineated a 2.5 km² productive area and a northeast-trending outflow tongue. Five wells (Mai-3D, -5, -6, -9, and -11) are capable of producing steam at commercial flowrates and pressures (Table 1). A third well drilled north of the high temperature reservoir, Mai-7, encountered a temperature reversal, and three holes drilled to the south were hot but impermeable. Table 1 shows the present status of Maibarara wells.

Table 1. MAIBARARA WELL DATA AND STATUS

WELL NAME	COMPLETION DATE	TD (m)		STEAM kg/s at 10 bars WHP	STATUS
		YD	VD		
1	08/13/77	1022	1022	-	
2	05/14/79	1676	1676	-	Non-commercial
79-11 SH	10/18/79	1608	1608	-	Slim hole, discovery well
3D	07/20/80	2980	2805	16	Commercial
4	01/05/81	3062	3060	-	Possible injector
5	02/16/81	2563	2475	15	Commercial
6	04/09/81	1981	1792	35	Commercial
7	07/06/81	2429	2179	-	
8	08/15/01	2195	2071	-	Possible injector
9	05/24/81	1679	1482	15	Commercial
10	06/07/82	2980	2740	-	Plugged and abandoned
11	02/19/83	2855	2701	6	Commercial

5. GEOCHEMISTRY

The reservoir fluids at Maibarara are neutral-pH sodium chloride liquids, however, low pH brine and cold dilute fluids occur at the periphery of the production area. Figure 4 shows the different fluid types found in Maibarara. An average of 1.5 wt % total dissolved solids (TDS) and 1.2 wt % non-condensible gases (*NCG*) characterize the reservoir fluids. These values are about double those found in the Bulalo reservoir (Villadolid, 1991). Reservoir chloride (Cl) concentrations range from 1500 to 6900 mg/kg. The Cl concentrations are highest in the north-central part of the proven productive area and decrease towards the north and south, indicating the outflow tongue and the presence of marginal cooler fluids, respectively (Figure 4). Bottom hole samples recovered acidic fluids in Mai-4 and Mai-7.

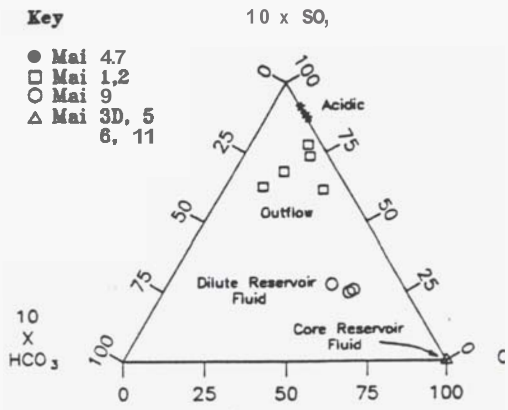

figure 4. Ternary diagram for Maibarara fluids.

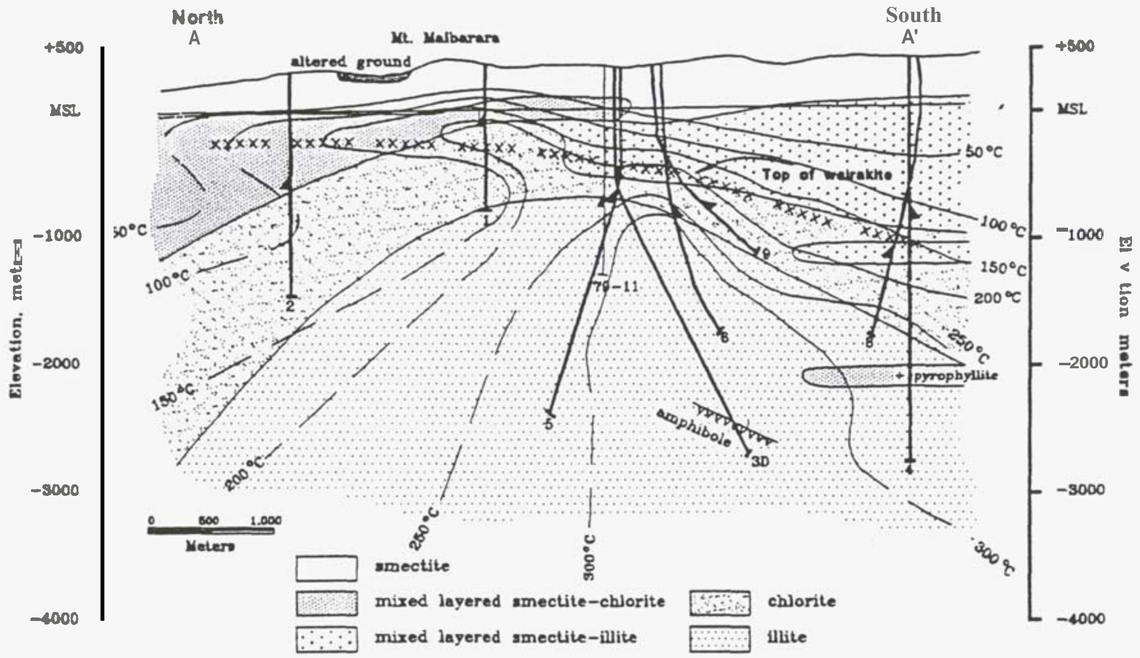

Figure 5. Hydrothermal alteration distribution in Moibarara. Isotherms are based on stable well temperatures.

6. HYDROTHERMAL ALTERATION

Interaction between hydrothermal fluids and the rocks results in the formation of a variety of hydrothermal minerals. In Maibarara, the observed minerals are typical of a benign chloride geothermal system (Browne, 1984). Figure 5 presents the distribution of hydrothermal alteration minerals in the Maibarara reservoir. The hydrothermal alteration is divided into four zones (from shallow to deep): smectite, a transition zone, chlorite, and illite. Within the chlorite zone is a subzone defined by the first appearance of wairakite; amphibole occurs in the illite zone. The transition zone contains interlayered illite-smectite and chlorite-smectite.

6.1 Deduced Reservoir Temperatures

Reservoir temperatures present in the Maibarara reservoir can be estimated from temperature-sensitive minerals. The deduced reservoir temperatures based on mineralogy are shown in Figure 6. Temperatures >220°C are indicated by the presence of illite and wairakite. In the core of the reservoir, higher temperatures (>290°C) are suggested by the presence of hydrothermal amphibole and anhydrite in Mai-3D, -6 and -11. In Mai-3D, the amphibole occurs 300m above the diorite pluton and appears to be associated with its intrusion. This correlation is observed elsewhere in Philippine geothermal systems (Reyes. 1990). In general. there is a good correlation between the observed mineral temperature indicators and measured temperatures in the known production area (Figures 5 and 6). However. cooling of at least 60°C on the northern margin of the field is suggested by the co-existence of wairakite (>220°C) with low-temperature interlayered smectite-chlorite clays (<160°C). On the southern margins of the reservoir. cooling of about 40°C is indicated by the presence of mixed-layered clays (Figure 5).

62 Fluid Camposition

Hydrothermal alteration minerals in the core of the reservoir such as smectite. chlorite, illite, calcium silicates (wairakite and epidote). calcite and anhydrite are typical of a benign chloride geothermal: system. These hydrothermal minerals were formed by fluids similar in composition to the fluids now observed in the reservoir. However, interlayered clays (smectite-chlorite and smectite-illite) suggest that cool dilute fluids are present at the periphery of the reservoir (Figure 5). Acidic fluids are suggested by a thin (<30m) discrete pyrophyllite-bearing zone at about -2140m msl in Mai-4. Bottomhole chemistry from this well confirmed the presence of acid-sulfate fluids (Hoagland, 1989; Abrigo, *et al.*, 1994). The acid zone appears to be localized along the NE-trending Kapos and San Antonio faults.

7. FLUID INCLUSION DATA

Fluid inclusions from cores and cuttings can show the changes with time in the thermal structure of a reservoir. A comparison of the fluid inclusion and measured temperatures indicates that considerable cooling has occurred in the northern part of the geothermal system, while no change has occurred within the productive reservoir. There is an excellent correlation between measured and fluid inclusion temperatures in Mai-6 (Figure 7), which is drilled into the core of the reservoir. In contrast, for Mai-7 (which penetrates the NE outflow tongue) there is a $\geq$ 90°C difference between fluid inclusion and measured wellbore temperatures. except at the bottom of the hole. This difference suggests that the Maibarara geothermal system has contracted by at least SO% over some geologic time span. In this process, the reservoir has effectively sealed itself from the surface, as indicated by the lack of significant thermal activity.

Apparent salinities calculated from fluid inclusions within the

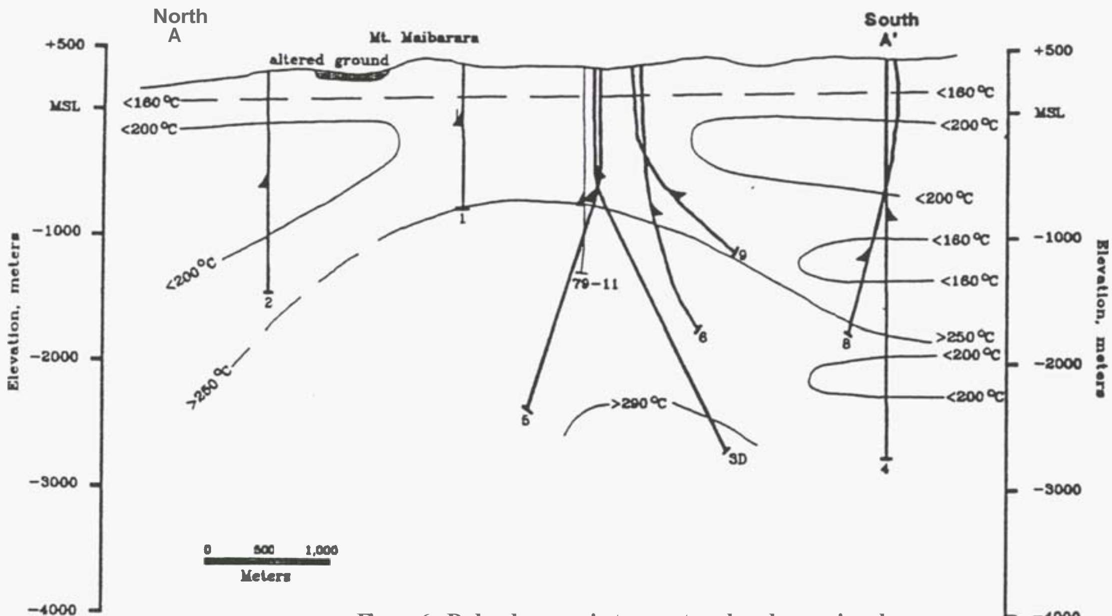

Figure 6. Deduced reservoir temperature based on mineralogy.

central portion of the reservoir are similar to the present composition (Abrigo *et al.*, 1994). However. significant differences of about 1000 mg/kg in chloride between fluid inclusions and the production fluids are found at the nonhern and southeastern margins of the field. where the influx of cooler water has been observed (Abrigo. *et al.*, 1994).

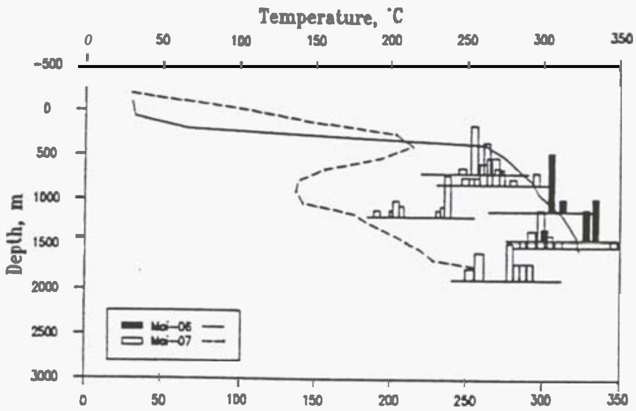

Figure 7. Fluid inclusion data showing considerable cooling has occurred north of the present geothermal system (Mai-7) and temperatures are similar in the current production area (Mai-6).

8. RESERVOIR CHARACTERISTICS

The Maibarara reservoir is a liquid-dominated, underpressured geothermal system (Abrigo. *et al.*, 1994). High temperatures (>300°C) exist in the core of the main production area. The matrix porosity of the reservoir rocks averages about 7.6%. with a range from 1 io 25%. Most permeable zones encountered by the production wells occur along vertical and near-vertical faults.

Data obtained from intermittent flow. tests done in 1982 (Fallon. 1985) and 1992 indicate that Mai-3D, -5. and -6 can initially produce sufficient steam for *25* MWe. assuming a conventional single flash power plant. Table I presents steam flowrates for the commercial wells. Using the heat-in-place method. calculated volumetric reserves are about 320 MW-years.

9. RESERVOIR AND GEOLOGIC CONCEPTUAL MODEL

The conceptual model of the Maibarara reservoir (Figure 8) is based on recently interpreted geoscientific, reservoir, and production data. The state or evolution of the system is inferred from an analysis of mineralogic and fluid inclusion data, fluid chemistry and well temperature profiles.

The Maibarara reservoir consists of a nearly symmetrical plume that originates near Mai-6 and flows towards the surface through vertical fractures. Permeability in the system appears to he fault controlled; the most important permeable structures are the NE-trending Nayon ng Kaplas and Kapos faults. E-trending Mnppinggon and Mai-9 faults, and the N-trending Bijiang fault (Figures 1 and 2). The temperature of the main upflow zone exceeds 316°C and reservoir chloride is about 7000 mg/kg. Reservoir fluids move vertically and laterally from a depth of >3050m below sea level in the core of the system to about -610m msl where they begin to cool and flow laterally towards the northeast. where they are progressively diluted. In contrast. changes in the composition and temperature of the fluids south of the productive reservoir are related to conductive cooling and inflow of cooler fluids. Deeper cooler dilute waters mix with reservoir fluids in the southeastern part of the field, causing the temperature reversals and less concentrated brine encouniered in Mai-9 and - 10. These dilute fluids flow west into the reservoir along the Mai-9 fault. Discrete zones of acidic fluids are encountered at Mai-4 and Mai-7 at -2134m msl and -1160m msl. respectively.

The top of the reservoir is at -610m msl as defined by the 220°C isotherm and/or the uppermost fluid entries in Mai-3D. -5, -6. -9 and -79-11. The western reservoir limit is bounded by the Maibarara fault which was crossed by Mai-11. The eastern boundary is between the total depth of Mai-6 and the cooler. tight rocks encountered by Mai-7 and -10 the gravity and MT resistivity anomalies also appear to delineate this boundary. Mai-5 delineiites the northern

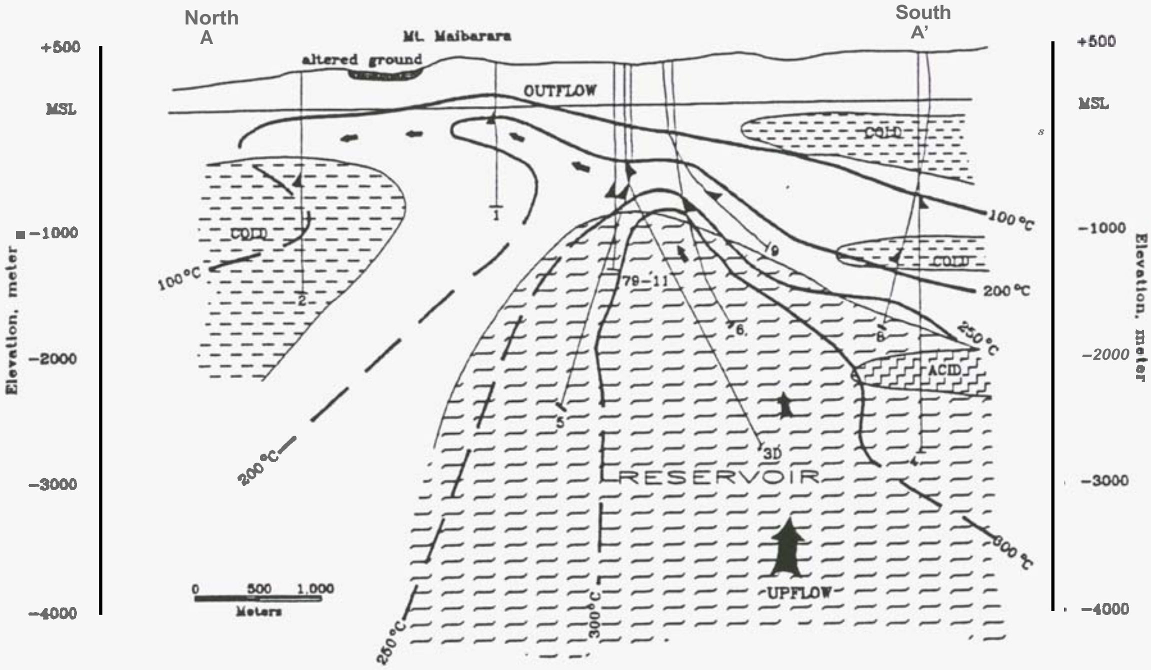

Figure 8. Conceptual model of the Maibarara geothermal system.

reservoir limit. as does Mai-9 to the SE. The southern limit occurs between Mai-3D and Mai-4, but it is probably closer to Mai-3D, as the 220°C isotherm is about 490m deeper in Mai-4.

It is assumed that the diorite pluton intersected at ≥-2439m msl will act as the reservoir floor due to its low porosity. No permeability was encountered by the wells drilled at or near pluton's margin. The deepest production encountered was in Mai-3D at -1854m msl.

The Maibarara reservoir has contracted naturally over time. based on current reservoir temperatures relative to historical ones (evidenced by fluid inclusion temperatures and alteration mineralogy). Temperature reversals in producing wells (e.g. Mai-9) and the presence of cooler dilute fluids migrating along faults intersecting the high temperature reservoir suggest a cautious approach to reservoir development at Maibarara. Once power generation begins, fluid chemistry and enthalpy must be frequently monitored to detect breakthrough of cooler or acidic fluids (c.f. Hoagland and Bodell. 1991: Gamhill and Beraquit, 1993) or injectate (Villadolid. 1991) into the central reservoir.

10. ACKNOWLEDGEMENTS

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11. REFERENCES

Abrigo. F. V.. Buban, A. C.. Sta. Maria. R. B.. Sussman. D.. and Mogen. P. G. 1994. Maibarara Geologic and Reservoir Model as of March. 1994, internal PGI report.

Browne. P. R L., 1984, Lectures on Geothermal Geology and Petrology. UN University. Reyjavik. Iceland. 87p.

Clemente. W. C. and Villadolid-Abrigo, F. L.. 1993, The Bulalo geothermal field. Philippines: Reservoir characteristics and response to production, Geothemiics. v. 22: 381-394.

Defant. M. J.. Maury. R. C. Joron. J. . Feigenson. M. D. Leterrier, J., Bellon, H., Jacques. D.. and Richard. M. 1990. The geochemistry and tectonic setting of the northern section of the Luzon Arc (The Philippines and Taiwan), Tectonophysics, v. 183: 187-205.

Fallon, J. P.. 1985. Field history and reservoir analysis of the Maibarara prospect. internal PGI report, 109 pp.

Gambill, D. T. and Beraquit. D. B. 1993. Development history of the Tiwi geothermal field. Philippines, Geothemiics. v. 22: 403-416.

Hoagland. J. R. 1988. Review of Maibarara geochemistry. internal PGI report, 13 pp.

Hoagland, J. R. and Bodell. J. M. 1991. The Tiwi geothermal reservoir: geologic characteristics and response to production. PetroMin., Jan.. pp. 28-35.

Oles. D. (Ed). 1991. Geology of the Macolod Corridor intersecting the Bataan-Mindoro Island Arc, the Geothermics, v. 22: 403-416. Philippines. German Research Society Report, 47 pp.

Pedersen. J. R. and Fernandez, J. C, 1985, Magnetotelluric investigation of the Mak-Ban contract area. Philippines. internal PGI report.

Reyes. A. G. 1990. Petrology of Philippine geothermal systems and application of alteration mineralogy to their assessment, J. Volcanol. Geotherm. Res., v. 43: 279-309.

Sussman. D. Javellana, S. P., and Benavidez, P. J.. 1993. Geothermal energy development in the Philippines: and Overview, Geothermics, v. 22: 353-367.

Villadolid. F. L, 1991, Applications of natural tracers in geothermal development: the Bulalo. Philippines experience. Proc. 13th New Zealand Geothermal Workshop. Auckland. pp. 69-74.

Wolf. J. A. and Self, S.. 1983. Structural lineaments and Neogene volcanism in southwestern Luzon. The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands. Pan 2 (ed. Hayes, P. E.), Am. Geophys. Union Monograph 27: 157-172.