Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

RESERVOIR MANAGEMENT STRATEGIES TO SUSTAIN THE FULL EXPLOITATION OF GREATER TONGONAN GEOTHERMAL FIELD, PHILIPPINES

Jose S. Seastres Jr., Noel D. Salonga, Virgilio S. Saw, and Dwight A. Maxino
PNOC-Energy Development Corporation, Fort Bonifacio, Makati City, Philippines

Key Words: exploitation, sustainability, pressure drawdown, reinjection, reservoir management strategy

ABSTRACT

The Greater Tongonan geothermal field, consisting of Tongonan and Mahanagdong reservoirs, has a total plant rated capacity of 702.6 MW. The full exploitation of this field to generate electricity for the Leyte-Cebu and Leyte-Luzon grids in July 1996 and July 1997, respectively, has induced fieldwide reservoir changes that could affect the capability of the field to sustain steam production in the long term.

Brine injection in the northwestern, southwestern and southern peripheries of the Tongonan reservoir was implemented since it was commissioned for production to the Leyte-Cebu grid. This strategy is necessary to provide fluid recharge to the reservoir particularly at the center of the field which hosts a shallow, two-phase zone. However, field pressure drawdown manifested by high enthalpy discharges (>2000 kJ/kg) of several production wells still persisted. As a consequence, the reservoir steam fraction in the upflow zone increased to as high as 5.0% from its baseline value close to 0%. In order to provide additional pressure support to the Tongonan reservoir and also address the environmental disposal problem, steam condensate fluids and waste brine will be injected in the northwestern and southwestern reinjection sectors of the field, respectively.

In Mahanagdong, while brine injection was confined in the northern and southern sectors, there is a natural inflow of cooler, shallow groundwater (<200°C) into the northwestern part of the reservoir. After around one year of commercial operation since the field was commissioned in July 1997, decline in fluid temperatures, salinities and bore outputs were observed in some production wells. Downhole temperatures indicate the invasion of cooler fluids from the west which percolated down through a northwest trending fault structure. Feasible solutions to this problem are the isolation of the conduit channeling the cooler fluid by cement plugging the top zone in the present wells and avoiding this structural conduit in the drilling of future production wells.

1.0 INTRODUCTION

The Greater Tongonan geothermal field, which covers an area of 40 km^2, consists of Tongonan and Mahanagdong reservoirs. An impermeable block, the Mamban plateau, which is characterized by low reservoir temperature (<200°C) separates the Tongonan reservoir from the Mahanagdong reservoir (Alvis-Isidro et al., 1993). The Tongonan reservoir is further subdivided into the Upper Mahiao, Mahiao-Sambaloran, Malitbog-South Sambaloran and Mamban sectors while the Mahanagdong reservoir is separated into Mahanagdong A and B sectors (Figure 1). The Tongonan-I power plant in the Mahiao-Sambaloran sector was the first plant commissioned in this field. It has been on commercial operation with a maximum rated capacity of 112.5 MW since June 1983. The field, however, can sustain 675 MW of steam production for a 25 year plant life based on numerical simulation studies (Sarmiento et al., 1993). To maximize power generation from Greater Tongonan due to increased energy demand from nearby island of Cebu, the first 77 MW unit of Malitbog-South Sambaloran power plant was commissioned in July 1996 together with the 125 MW Upper Mahiao power plant. In July 1997, the other 2 x 77 MW units of Malitbog-South Sambaloran, the 120 MW Mahanagdong-A and 60 MW Mahanagdong-B power plants were commissioned to supply the power requirements of the main island of Luzon. An additional output of 49.5 MW was provided by the optimization of power plants through dual flash cycle at high pressure (1.20 MPa) and lower pressure steam separation (0.70 MPa) from Tongonan I (17 MW), Mahanagdong A (12 MW), Mahanagdong-B (6 MW) and Malitbog Bottoming Plant (14.5 MW).

The Greater Tongonan field has been producing a maximum of 693 MW since July 1997 to the Leyte-Cebu and Leyte-Luzon power grids. All of the power plants have been operated since that period except the 4.56 MWe binary plant in Upper Mahiao which was not commissioned due to insufficient brine supply. The massive exploitation of this field has induced changes that could affect the capability of the reservoir to sustain steam production to the power plants in the long term. In order to address the sustainability of the field, reservoir management strategies were formulated based on the chemical and physical responses of the Greater Tongonan reservoir to full exploitation.

2.0 PRE-COMMISSIONING HYDROLOGICAL PROFILE

The subsurface hydrological profile (Figure 2) prior to the start of full exploitation of Greater Tongonan in July 1996 indicates an upwelling zone of high temperature (300°C) and highly mineralized fluids (~ 9000 mg/kg chloride level) centered near well 401 (Figure 3) in the Upper Mahiao sector of Tongonan reservoir (Seastres et al., 1996; Salonga et al., 1997). From Upper Mahiao, the reservoir outflows preferentially to the southeast towards the Malitbog sector as indicated by declining field temperature (~200°C at –1000m RSL) and mineralization (~4000 mg/kg reservoir chloride concentration). The reservoir fluids also outflow to the northwest towards the 408/4RC4 area (Figure 1). The initial field exploitation of the Tongonan reservoir to supply steam to the 112.5 MW Tongonan power plant in June 1983 had induced field pressure drawdown. This condition was facilitated by a total mass extraction of >300,000 tons/yr from

1983 until 1989 (Seastres et al., 1999). However, when the gross energy generation increased to >500,000 MW-hr/yr in 1990 from ≤450,000 MW-hr/yr in 1989, reinjection mass breakthrough occurred in the Mahiao-Sambaloran sector due to the corresponding increase in wastewater load (>350,000 tons/yr). The inflow of reinjection fluids from 1R8D, 2R3D and 2R4D (i.e. 30% to 58% of the reservoir fluid based on chloride mass balance calculations) to the production wells caused bore output deterioration in wells closest to the reinjection sink (101, 103, 105, 213, 214 and 215). However, to arrest further thermal decline in these wells, the total reinjection load was reduced from 140 kg/s to 90 kg/s in wells 2R3D and 2R4D in September 1995. This strategy initiated the resurgence of pressure drawdown in the Tongonan reservoir. The state of the Tongonan reservoir prior to the start of full field exploitation in July 1996 indicates that pressure drawdown is centered (maximum of 2 MPag) in the upflow region (i.e. within 401) as characterized by the 7.5 MPag isobar contour (Figure 3).

In the Mahanagdong reservoir, the major upflow zone, located near MG3D, is characterized by fluid temperature as high as 300°C (Figure 5) and a reservoir chloride concentration of 4000 mg/kg. The deep reservoir fluid outflows to the south with temperature as low as 200°C. An acidic region (discharge pH <4.0) was encountered within the MG-B/3 sector (Herras et al., 1996) which is characterized by high reservoir chloride (2700-4200 mg/kg) and high reservoir sulfate (>100 mg/kg). The migration of acidic fluids from this sector to Mahanagdong production wells was considered unlikely since reservoir pressure profile at different elevations suggests that the wells which encountered acidic fluids are not hydrologically connected to the Mahanagdong production wells (Seastres et al., 1996).

At the western sector of the Mahanagdong reservoir, the field temperature contours at –1000m relative to sea level indicate the presence of shallow groundwater. With further field pressure drawdown in response to exploitation, it was predicted that the breakthrough of cold meteoric water would cause temperature deterioration in the wells closest to this sector.

3.0 RESERVOIR RESPONSE TO FULL EXPLOITATION

The physical and chemical changes in response to full exploitation starting in July 1996 upon commissioning of the Leyte-Cebu grid (202 MW) were evaluated based on fluid chemistry trends, massflow data, temperature and pressure profiles of the production wells. In July 1997, these reservoir changes were enhanced due to increased fluid withdrawal during the commercial operation of the Leyte-Luzon power grid (334 MW).

3.1 Tongonan Reservoir

The massive field exploitation in Tongonan starting in July 1996 has further induced pressure drawdown that was already observed prior to this period (section 2.0). The magnitude of pressure drawdown, which was again enhanced in July 1997, is manifested by pressure decline of as much as 4.0 MPa in the monitor well 106 from March 1995 to March 1999. The liquid column in this well changed to a highly two-phase condition. Gas equilibria diagram had been used to assess the relative expansion of the vapor phase based on the following FT-HSH2 equilibria reaction (Siega et al., 1999):

FT (Fischer Tropsch): $CH_4 + 2H_2O = CO_2 + 4H_2$
HSH2: $^5/_4\ H_2 + {^3/_2}\ FeS_2 + {^3/_4}\ Fe_2O_3 + {^7/_4}\ H_2O = 3H_2S + Fe_3O_4$.

On a field-wide basis, the reservoir steam fraction based on this gas equilibria reaction indicates a vapor gain between 1% to 5% in April 1999 (Figure 4) for most production wells from close to liquid saturation (y=0) during the baseline period (~1984). This is consistent with the expansion of steam zone as suggested by the reduction of partial pressure of dissolved CO_2 gases due to the decrease in volume of water fraction (Figure 7). Only the wells in Malitbog, which are farthest from the center of drawdown, are still discharging liquid dominated fluids with an average enthalpy of <1600 kJ/kg. Several wells in the Tongonan reservoir are now characterized by high enthalpy (>2000 kJ/kg), two-phase fluid discharges. In fact, the Mahiao-Sambaloran wells which encountered a major breakthrough of reinjection fluids (1993-1994) have now fully recovered from reinjection fluid returns and most wells are currently discharging high enthalpy fluids (2100-2700 kJ/kg).

Although major pressure drawdown has occurred on a fieldwide basis in the reservoir, cold meteoric water inflows anticipated from the vicinity of wells 102, 409 and 509 were not encountered nor reinjection fluid breakthrough from the northwest reinjection sector (4RC4) since July 1996. This condition suggests that this sector has poor hydrological connection with the Tongonan production sector. Reinjection breakthrough, however, was detected in some production wells (e.g. 503, 508 and 514D) in Malitbog due to the utilization of 5R7D in May 1997. Reinjection fluid returns stabilized and subsequently declined when 5R7D was not utilized for waste brine injection. Some production wells (509 and 510D) near the South Sambaloran sector recently encountered an increase in discharge enthalpy of ~150 kJ/kg (March 1999) indicating that drawdown is gradually expanding to this sector.

3.2 Mahanagdong Reservoir

The major steam withdrawal upon commissioning of Mahanagdong power plants in July 1997 facilitated the inflow of shallow groundwater (i.e. particularly in Mahanagdong A production sector) from the northwestern sector of this field (Figure 5). Temperature deterioration was first detected in MG23D based on declining silica (quartz) geothermometer (Fourneir and Potter, 1982) from 270°C to 250°C in June 1998 which corresponds to a decrease in reservoir chloride level from 2700 mg/kg to 2560 mg/kg and increase in reservoir calcium concentration from 25 mg/kg to 40 mg/kg. Cooler fluids from the upper permeable zone at 1400-1500 mMD (i.e. MD indicates the actual measured depth of a directional well) of this well only dominated the discharge upon isolation of the bottom permeable zone by calcite blockage at 1470 mMD. However, measured temperature surveys after clearing of calcite deposits through workover operation in June 1999 indicate the persistence of cooler fluid inflow (~200°C) from 1500 mMD (July 1999 temperature surveys). Shallow groundwater inflows were subsequently detected in MG-1 and MG25D. Fluid temperatures decreased in MG1 based on silica (quartz) temperature from 271°C to

262°C in May 1999. For MG25D, which cannot sustain discharge for production, a downflow of cold meteoric fluids with measured temperature of 220°C (April 1999) from 1200 mMD to 1550 mMD was observed. The conduit channeling the movement of groundwater from the northwest of Mahanagdong to these wells is believed to be the Lower Mahanagdong Fault (Figure 5). The only remaining production well that intersected this fault but had no indication of cold meteoric water component yet is MG33D.

The massflow declines noted in Mahanagdong-A wells (MG1, MG7D, MG19D and MG23D) were also attributed to calcite blockages. An evaluation of the calcite saturation indices based on aqueous speciation computer program WATCH (Arnorrson et al., 1982) shows that these wells are primarily oversaturated with respect to calcite (i.e. calcite saturation indices as high as 1.0, Figure 6). Well MG23D has a decreasing calcite saturation with time but this is interpreted to be due to the undersaturated state of thermal fluids after depositing calcite. The presence of calcite deposits were confirmed based on sample recoveries from downhole scraper runs and discharge ejecta.

In Mahanagdong B, field pressure drawdown was observed from wells sharing common fault structures. These wells consisting of MG27D, MG29D, MG28D and MG31D in MG-DL pad (Figure 1) are adjacent to each other and are interconnected through either North Mamban or Ewex and Malitbog Faults. Similarity in their fluid chemistry composition (e.g. reservoir chloride ~2800 mg/kg for MG27D and MG29D) was recognized in these wells. Reservoir pressure profiles confirmed a pressure decline ranging from 1.0 to 2.0 MPa(g) at depths of 1600-2500 mMD in 1998 relative to the 1996 downhole data for Mahanagdong-B production wells.

4.0 RESERVOIR STRATEGIES TO SUSTAIN STEAM PRODUCTION

Field pressure drawdown has not yet affected the capability of the reservoir to provide steam to the Tongonan power plants since the Leyte-Cebu grid commissioning in July 1996. Existing wells in the Tongonan reservoir can produce a total of 5140 tons/hr (June 1999) of steam which is much more than the total power plant requirement of 3628 tons/hr.

Pressure drawdown has resulted in the vertical and lateral expansion of the steam zone that sustains the steam supply for all Tongonan power plants. However, it is believed that the steam expansion has already attained its optimum limit since the current temperature of boiling based on SNHC gas equilibria (Dacillo et al., 1998) has already reached the deep reservoir temperature level of 300°C. If this is the case, the Tongonan reservoir may encounter an irreversible loss of steam supply if artificial fluid recharge from reinjection and steam condensate fluids to the production sector cannot be induced. However, in order for the recharge to be effective, the injected fluids should be sufficiently reheated before reaching the reservoir.

Although reinjection fluid returns have been detected in Malitbog, it was not observed in areas where extensive drawdown has occurred (i.e. Upper Mahiao, Mahiao-Sambaloran and South Sambaloran sectors). As a consequence, the total reinjection load of the Tongonan reservoir was reduced by more than 50% from 1845 kg/s (August 1997) to 830 kg/s (June 1999). If adequate fluid recharge cannot be sustained, the Tongonan reservoir will dry-out and the steam capability of the field will be severely affected.

The reservoir management strategy to sustain steam production in the Tongonan reservoir involves the shift of wastewater injection from 4RC4 reinjection pad (Figure 1) to the Mahiao-Sambaloran reinjection sector. The present brine load at Mahiao-Sambaloran (Figure 7) is around 190 kg/s (June 1999) from as high as 390 kg/s (June 1996). To provide reinjection fluid recharge to this sector, the wastewater load available for injection from South Sambaloran is 230 kg/s which will be optimized depending on the response of the production wells in the Mahiao-Sambaloran sector. For Upper Mahiao, the 270 kg/s steam condensate fluids presently being discharge to the river will be injected in the 4RC4 reinjection wells. This strategy may not only address the fluid recharge requirement but also the environmental disposal problem.

With decreasing brine load from Malitbog and South Sambaloran sectors (Figure 7), these sectors can only supply 544 kg/s (June 1999) of brine to the 14.5 MW Malitbog bottoming plant for second flashing which is less than the requirement of 670.5 kg/s. It is anticipated that field pressure drawdown will further deteriorate if no adequate recharge can be provided. The reservoir cannot, therefore, sustain the brine requirement of the bottoming plant. If such condition will persist, additional steam from the first stage flashing in Malitbog-South Sambaloran separator vessels can be used to supply the steam requirement of this power plant. This option, however, needs a modification of the steam/gas extractor system of the bottoming plant to accommodate the high NCG (Non-Condensible Gas) level (~1.10% wt) of the steam from the first flash relative to the NCG plant limit of 0.10% wt.

The Mahanagdong reservoir has been affected by the incursion of shallow groundwater and calcite deposition in several production wells. However, the bore outputs of the production wells (MG23D, MG1, MG19 and MG7D) were recovered through workover operations conducted from June to August 1999. Cement plugging of the conduits channeling the inflow of shallow groundwater through the northwest trending Lower Mahanagdong fault in MG23D and MG25D were also implemented. Production wells to be drilled to sustain the steam supply should be designed to avoid this fault structure.

In addition to the drilling strategy, the steam pipeline supplying the steam requirements of the power plants within the Tongonan reservoir will be interconnected to the steam pipeline of Mahanagdong by July 2000. Additional power load of 20-60 MW can be supplied from the Tongonan field through the steam pipeline interconnection project. This project will be quite valuable in providing an operational flexibility to supply steam from sector to sector. The generating capacity of the Greater Tongonan reservoir can be, therefore, maximized. However, as a long-term strategy in sustaining the Mahanagdong reservoir, the eastern sector beyond the current production block should be drilled for future steam production requirements.

5.0 CONCLUSIONS

The full exploitation of the Greater Tongonan geothermal field starting in July 1996 has induced massive pressure drawdown in the Tongonan reservoir and inflow of shallow groundwaters in the Mahanagdong reservoir. Although the steam availability of Tongonan was not yet affected by field pressure drawdown, the reservoir may not sustain long term steam production without adequate fluid recharge. Additional brine injection in the Mahiao-Sambaloran sector and steam condensate injection in the Upper Mahiao sector may provide recharge to the deep reservoir. However, these fluids must be sufficiently reheated before reaching the reservoir.

The incursion of shallow groundwater, which was aggravated by calcite deposition, has affected the Mahanagdong reservoir. Mechanical work-over of calcite deposits using a drilling rig and cement plugging the cold meteoric water conduit in the existing production wells were implemented to address these field operational problems. Drilling of new production wells should be designed to avoid the structural channel of this shallow groundwater.

ACKNOWLEDGEMENTS

The authors are indebted to the PNOC-EDC management for allowing the publication of this paper. We also extend our gratitude to the LGPP Geoservices Staff for technical support in the completion of the manuscript.

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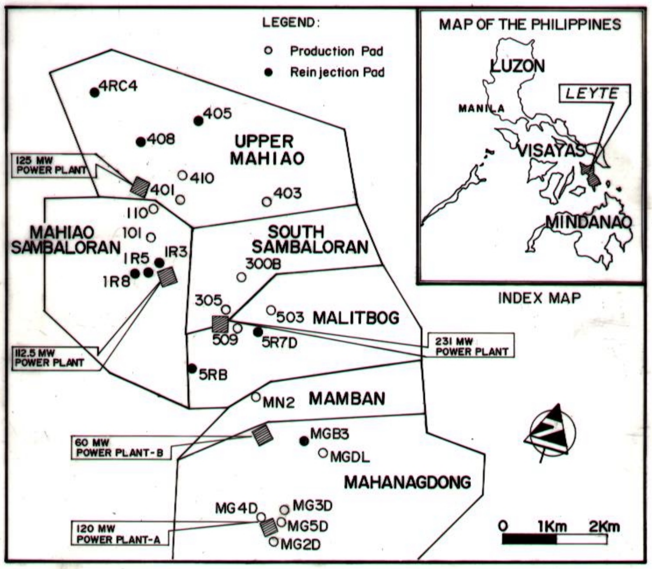

Figure 1. Map of the Greater Tongonan geothermal field showing the sectoral boundaries of the field, location of the power plants and selected production/reinjection pads.

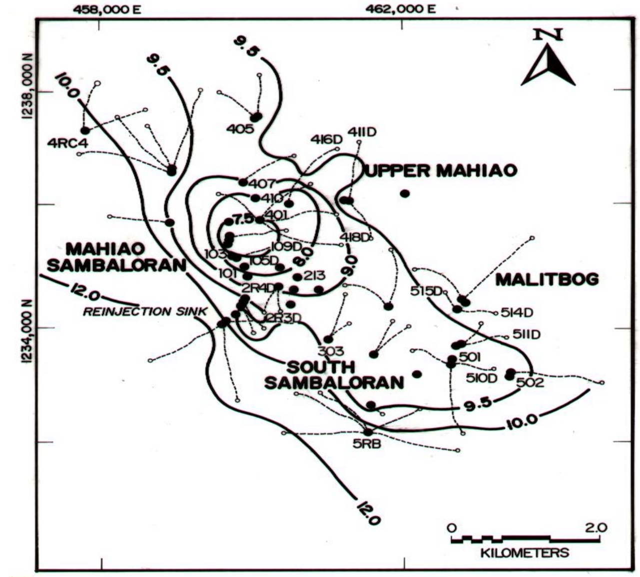

Figure 3. Field pressure contours of Tongonan reservoir in MPa(g) at –1000m relative to sea level.

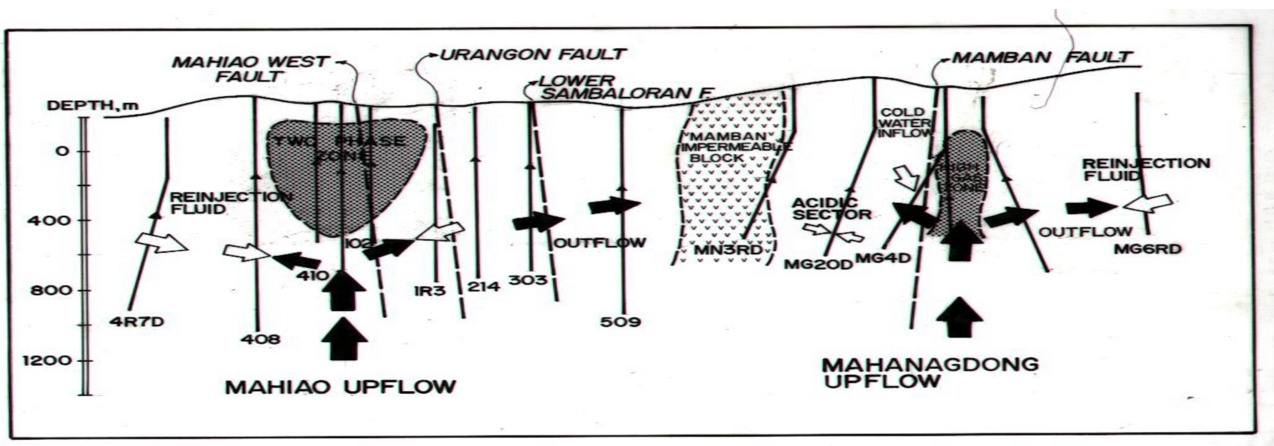

Figure 2. Conceptual hydrological model of Greater Tongonan prior to full exploitation

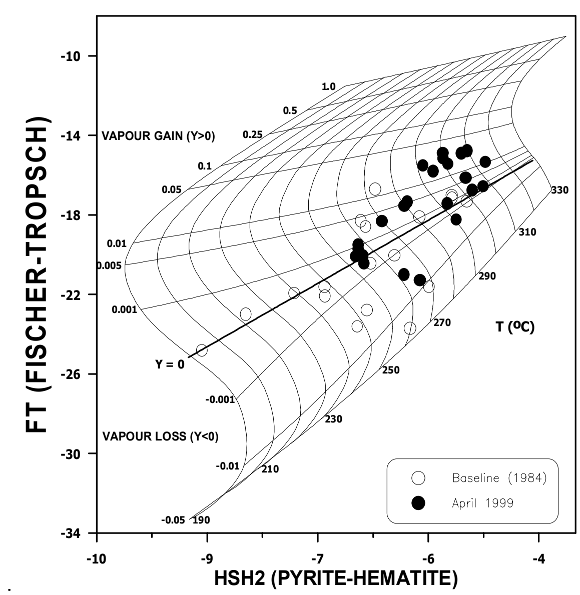

Figure 4. FT (Fischer Tropsch) – HSH2 (pyrite-hematite gas equilibria) grid diagram for production wells of Tongonan reservoir. Legend: **Y**-refers to reservoir steam fraction, **T(°C)** – fluid temperature expressed in degree Celsius.

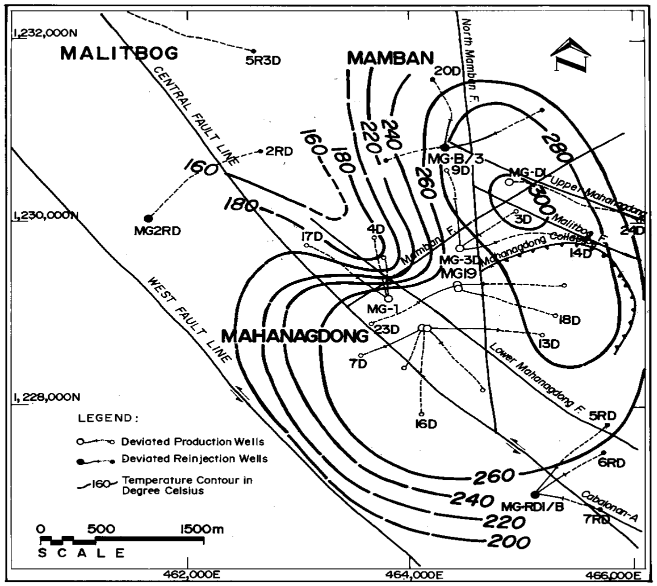

Figure 5. The field temperature contour map of Mahanagdong reservoir at –1000m relative to sea level based on measured downhole temperatures in 1996.

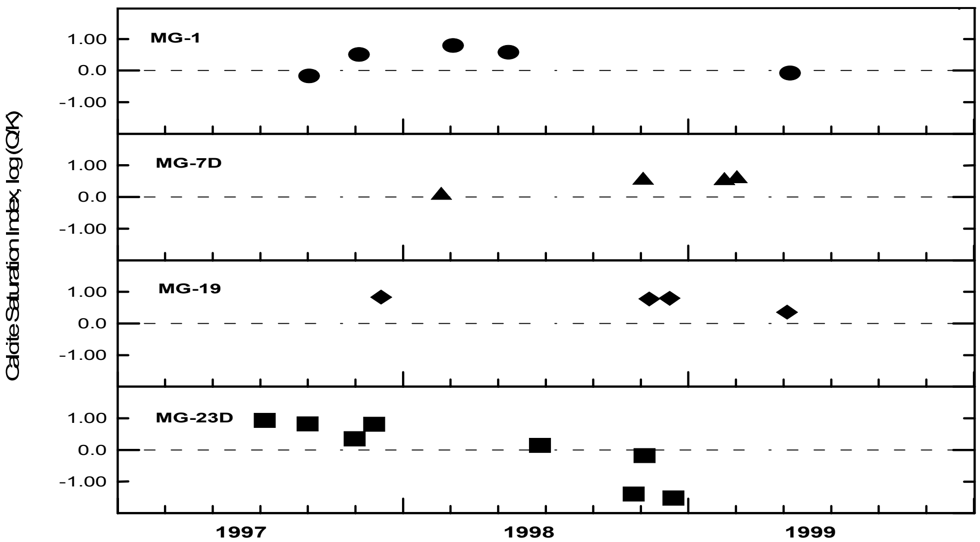

Figure 6. Calcite saturation indices of selected Mahanagdong-A production wells

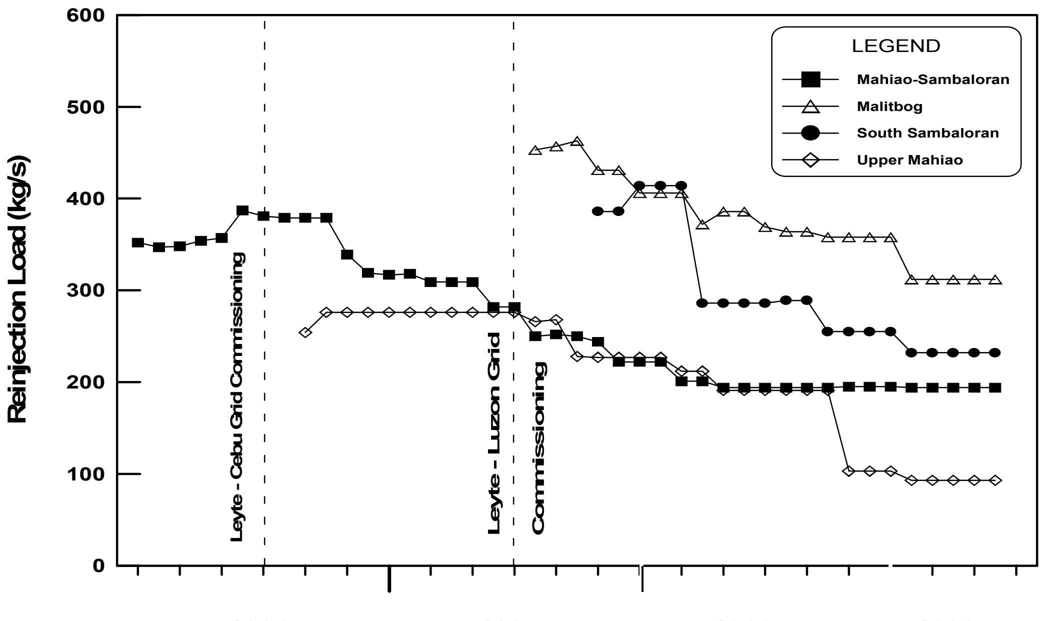

Figure 7. Reinjection loads trends of Mahiao-Sambaloran, Malitbog, South Sambaloran and Upper Mahiao sectors of the Tongonan reservoir.