PROCEEDINGS, 23rd Annual PNOC-EDC Geothermal Conference
Hotel Inter-Continental, Makati City, Philippines, March 13-14, 2002

APPLICATION OF STABLE ISOTOPES IN MONITORING THE INFLOW OF COOLER WATERS IN THE MAHANAGDONG GEOTHERMAL FIELD, PHILIPPINES

Edwin B. Herras

PNOC Energy Development Corporation, Merritt Road, Fort Bonifacio, Metro Manila 1201, Philippines

ABSTRACT

The use of stable isotope with other water and gas chemistry tools has been effective in monitoring reservoir processes affecting the Mahanagdong geothermal field. The dominant reservoir process observed in the Mahanagdong field since the start of its exploitation in 1997 is the inflow of cooler fluids which include the injected brine and groundwaters. Examples of these are the following ; a) inflow of cooler groundwaters in well MG-23D believed to be coming from the Paril area; b) injection returns from MG-83 injection sink affecting wells MG-30D, MG-28D, MG-26D and MG-31D c) inflow of degassed and dilute cooler waters observed in wells MG-3D, MG-14D, MG-30D and MG-31D believed to be condensate fluids from the nearby well, MG-9D. However, recent stable isotope data collected from the latter production wells reveal that the major component of this inflow is groundwater typical of Paril area. Only well MG-3D showed an indication of mixing with condensate type of fluids based on its shift in $\delta^{18}O$. *To address these concerns on cooler water inflow, changes in the presenf production and injection well strategies were implemented in order to sustain the operation of Mahanagdong field.*

1.0 INTRODUCTION

Mahanagdong is one of the geothermal fields that lie along the Philippine Fault in the island of Leyte. It is found southeast of Tongonan geothermal field. Both fields collectively form the Greater Tongonan Field covering an area of 40 km^2 which lie along a northwest trending chain of Quaternary volcanoes in the island of Leyte (Figure 1). At present, there are 20 production wells in Mahanagdong that supply steam to: (1) the 120 MW main plant and the 12 MW optimization plant in Mahanagdong-A sector, and (2) the 60 MW main plant and the 6 MW optimization plant in Mahanagdong-B sector.

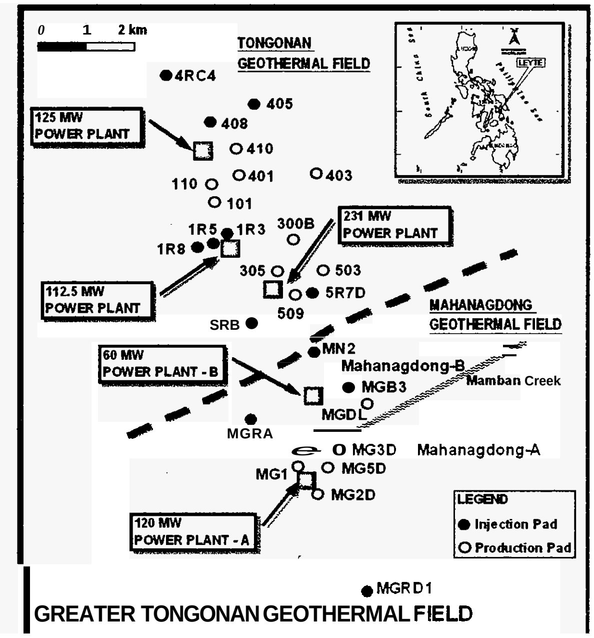

Figure 1. Map of the Greater Tongonan geothermal field composed of the two fields of Tongonan and Mahanagdong.

Isotopic investigations of the Mahanagdong geothermal field include works by Hulston et al. (1982), Alvis-Isidro et al. (1993) and Salonga and Siega (1996). Hulston et al. (1982) reported that the cooler Thermal Gradient Exploratory (TGE) wells have isotopic composition similar with meteoric waters and MG-1 had a smaller $\delta^{18}O$ shift relative to Tongonan wells. Alvis-Isidro et al. (1993) established that the Mahanagdong geothermal system is separate from the Tongonan geothermal field. An extensive geochemical work by Salonga and Siega (1996) established the baseline stable isotope distribution across the field and identified the potential problems associated with the

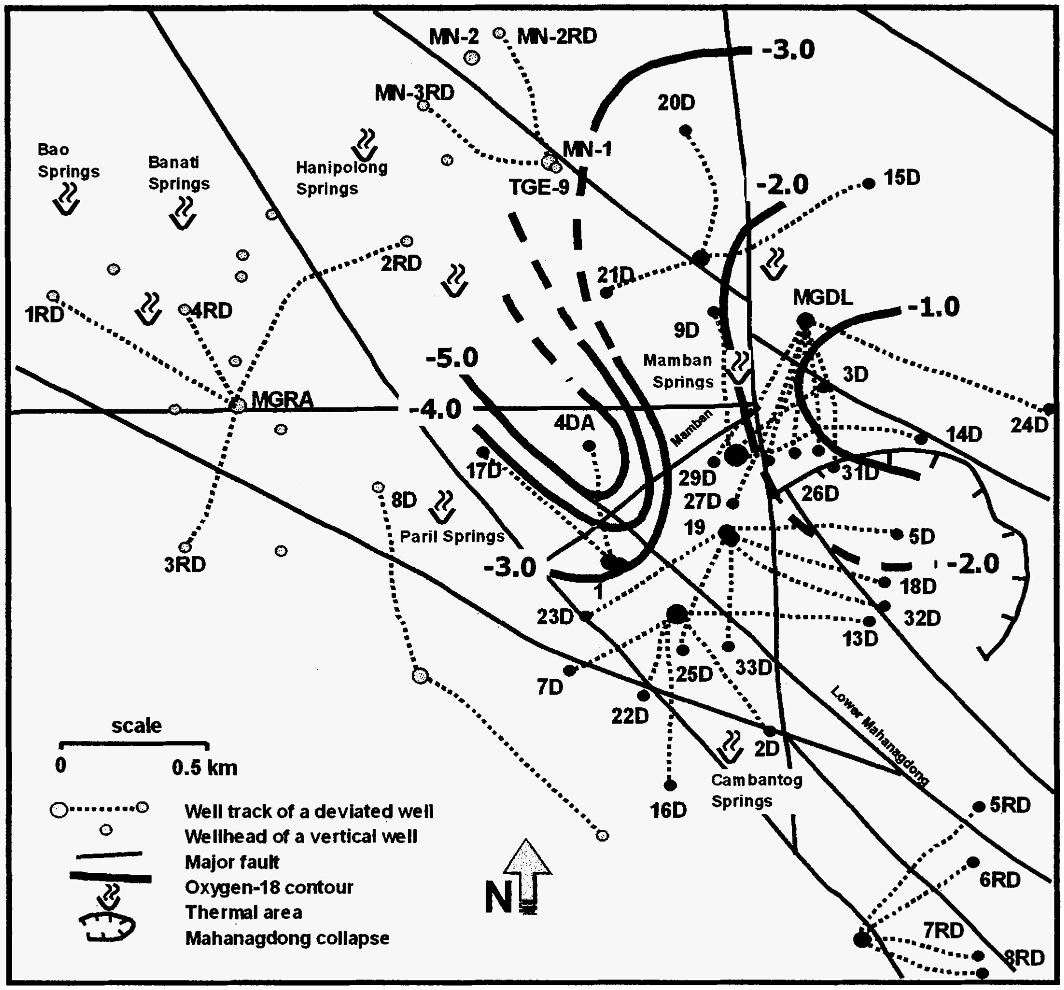

Figure 2. Baseline iso-δ^{18}O contour map of Mahanagdong field (values in per mille VSMOW) (after Salonga and Siega, 1996).

exploitation of the reservoir. One of which is the incursion of cold groundwater into the deep levels of the reservoir in the northwestern quadrant of the field.

This paper assesses the isotope data during the production phase of the field with the objective of identifying the source of the cold fluid inflow affecting the Mahanagdong wells. It also presents a review of the conceptual hydrological flow model of Mahanagdong specifically on the area affected by inflow of cooler water.

2.0 NATURAL STATE HYDROLOGICAL FLOW MODEL

Water and steam condensate samples using webre separator have been collected since the early 1980s for isotopic analyses during discharge tests of deep wells in Mahanagdong. The distribution of the stable isotopes across the Mahanagdong geothermal field is depicted in iso-δ^{18}O contour map in Figure 2. The most isotopically enriched region is enclosed by -1.0960 contour in the eastern side of the field, which include wells MG-3D and MG-14D. This area is proximate to the Mamban thermal area and to the Mahanagdong collapse structure. It also marks the hottest sector of the field, which has measured temperature of 280-300°C at -1000mRSL. The reservoir chloride in this sector is around 3800-4000 mg/kg. Because of stable isotopes and fluid temperatures, these wells are presumed to be representative of the parent fluids in Mahanagdong field. The configuration of the iso-δ^{18}O contour from MG-3D suggests oufflow of thermal fluids towards the northwest, south and southwest areas. Oufflowing fluids to the north are

Sample Source	Date	Cl	Ca	Mg	SO_4
MG-23D D/H **sample**	**Mar-Apr** ‘99	8-40	184-289	16-34	750
Steam-heated groundwater (Paril HS30)	**May-Oct** ‘97	0-188	198-224	48-96	1750-4330
MG-A **Plant Condensate Fluids**	**Apt. 5,** ‘99	1.2	6.0	0.04	80
	Jan 3, 01	53	3.6	0.58	1/05
	Aug 18, 01	13.1	3.6	1.34	91.2
Thermal pond brine	**Apr. 5,** ‘99	4400	31	1.22	84
Surface water (Mamban River)	**Mar.** 3, ‘99	2.4	2.0	2.12	45

characterized by reservoir Cl of 3000-4000 mg/kg and temperatures of 260-280°C. These fluids are slightly depleted of stable isotopes that range from -3.0 to -2.0‰ $\delta^{18}O$. Fluids flowing southeast have similar temperatures of 260 to 280°C and Cl_{RES} of 2500 to 3000 mg/kg.

A tongue-like indention of iso-$\delta^{18}O$ contour manifested the inflow of cooler groundwater from the northwestern sector (Figure 2) of Mahanagdong. Wells MG-4DA and MG-17D, which encountered these cooler waters, have temperatures of less than 240°C, (i.e. the coolest among the production wells). They also discharged the most diluted fluids with less than 2500 mg/kg Cl_{RES} and also the most isotopically depleted waters with less than -3.0‰ $\delta^{18}O$.

3.0 INFLOW OF COOLER FLUIDS DURING FIELD EXPLOITATION

The Mahanagdong Fluid Collection and Disposal System (FCDS) upon its commissioning in 1997 consisted of 13 production wells feeding steam to the 120 MW Mahanagdong-A main plant while the injected brine is accommodated into five injection wells in an off-field pad, MG-RDIB, southeast of the area (Figure I). Well MG-4DA and MG-17D, located in the western part of the field, receives the plant condensates during the start (July 1997) of steam production in Mahanagdong. The 60 MW Mahanagdong-B power plant, on the other hand, was supplied by seven production wells located mostly on the northern part of the field, while its brine is disposed north of area at pads MN-1 and MG-B3.

A year after its commissioning, the Mahanagdong field was characterized by an unprecedented response of the reservoir to production marked by the occurrence of blockages in some wells, cooler water intrusion, gas expansion and feed sharing among neighboring wells. All these changes contributed to varying extent on the problem of steam shortfall in the MG-A main plant.

3.1 Inflow of Groundwaters

Well MG-23D exhibited a significant decline in output in May 1998 following the Occurrence of a blockage that isolated the wells bottom permeable zone. This wa s reflected in the changes in the chemistry of the well. Cooling was noted as the quartz geothermometer declined from 271°C (25 May 1998) to 255°C (4 September 1998). During the same period, chloride also declined from 2700 mg/kg to 2560 mg/kg while calcium and sulfate increased from 28 mg/kg to 35 mg/kg and 20 mg/kg to 43 mg/kg, respectively. This observation suggests the intrusion of a genetically different fluid characterized by high SO_4 and high Ca but low chloride and low fluid temperature (quartz).

In January 1999, the well was cut-out due to the unscheduled shutdown of the FCDS. Since then, the well did not sustain discharge after several attempts due to blockage and further thermal deterioration observed just below the Production Casing Shoe (PCS). When the injection of condensate was shifted to MG-RDIB in April 1999, the well did not show recovery from the effects of cooler fluid inflow. The downhole samples collected at the depth where cooling was observed revealed fluids having very low chloride with high calcium and sulfate content (Table 1), which is similar to the steam-heated groundwaters of Paril hot springs. This suggests that the cold, diluting fluids originated either from the top of the reservoir or from the northwestern periphery of the field.

Furthermore, the isotopic data showed evidence of cooler water intrusion as indicated by depletion of $\delta^{18}O$ from -2.0 ‰ (18 June 1997) to -2.6 ‰ (27 July 1998). The shift in the data point of MG23D (Figure 3) showed that the chemistry

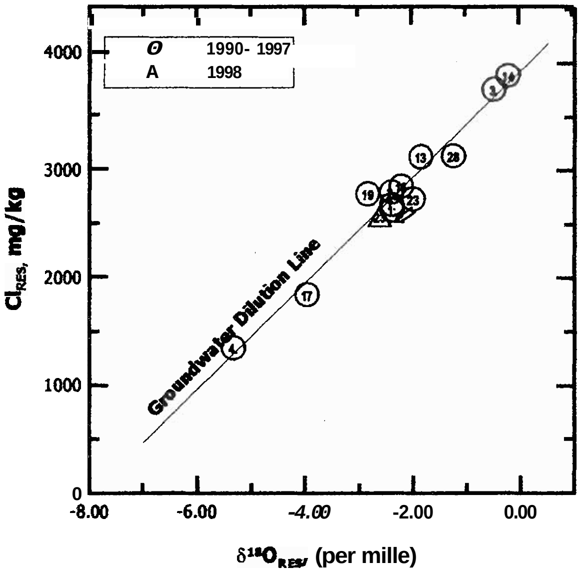

Figure 3. Crossplot of $\delta^{18}O$ and chloride showing the shift of MG-23D data point towards that of MG-4DA and MG-17D, the wells infested with cooler fluids (after Seastres et al., 1999).

of the well shifted towards the isotopic composition of MG17D type of fluids in the west. It ruled out the postulated ingress of plant condensate injected in MG4DA/MG17D as the present data points shifted away from the isotopic signature of the plant condensates.

Based on the results from chemistry and isotope data, well MG-23D underwent rig workover in June and August 1999. The first workover cleared aut calcite scales at 1100-1150m, 1462-1552m, and 1552-1675m. The second workover involved squeeze cementing which sealed off the identified cooler fluid entries at 650m and 1300m. The well sustained discharge after workover and its present chemistry suggests recovery from the inflow of cooler fluids and greater contribution from the bottom feed with its quartz geothermometer already at 265°C (November 1999).

Other wells affected by the inflow of groundwaters are MG-1, MG-27D and MG-29D. Well MG-1 similarly exhibited a decline in its quartz fluid temperature ($TSiO_2$) and reservoir chloride after its bottom was isolated by a blockage in May to August 2000. Well MG-27D showed a marked $TSiO_2$ drop of 7°C in December 1999. Well MG-29D exhibited a 10°C drop in $TSiO_2$ and 700 mg/kg reduction in reservoir chloride.

Radioisotope(^{125}I) tracer tests conducted in well MG-4DA in October 1999 showed positive tracer returns in wells MG-27D, 29D, 28D, 26D, 31D and 30D (Delfin et al., 2001). The preferential flow of Paril groundwater towards the northeast supports the chemical trends exhibited by these affected wells. Previous NaFl tracer tests conducted in April 1999 established a hydrological connection between MG-17D. and well MG-23D and MG-25D through the Lower Mahanagdong fault. Results from the ^{125}I tracer tests are different from the previous NaFl tests because of the large pressure drawdown (-5 MPa) that has taken place in the northeast sector since the start of exploitation.

3.2 Inflow of Brine Injection Returns

In the last quarter of 1999, some of the wells in the northwest showed indications of the mixing of injected brine. Well MG-30D and 31D showed an increase in reservoir chloride to 4100-4500 mg/kg and decline in its total discharge CO_2. This was coupled with a decline in its deep fluid temperature (T-Quartz). The brine injected in the north having a chloride content of about 4700 mg/kg can affect such increase in chloride level. The same fluids encroaching MG-DL wells were also betieved to be affecting neighboring wells MG-3D and MG-14D based on the decrease in its quartz geothemometer and total discharge CO_2.

To arrest the inflow of injected brine, the brine load of about 100-120 kg/s from the nearby injection well, MG-21D was transferred to the off-field Mamban-1 injection wells in August-September 2000. Furthermore, the injection of 120-150 kg/s of brine from the thermal pond into MG-9D was consequently transferred to MG-B3. MG-SD was instead utilized as injection well for the condensate (est. 30-90 kg/s) from Mahanagdong-A main power plant.

During the first quarter of 2001, MG-3D, MG-14D, 30D and 31D showed slight recoveries from the mixing of injected brine based on their stabilized chemical trends. Well MG-3D temporarily showed stabilized trends in its quartz geothermometer of 270°C from its previously declining trend. MG-30D and MG-31D also displayed recovery after its Cl_{RES} levels dropped back to its original level of 3600 mg/kg. However, the recoveries were short-lived as the chemical trends continued to decline the succeeding months. This time the wells showed

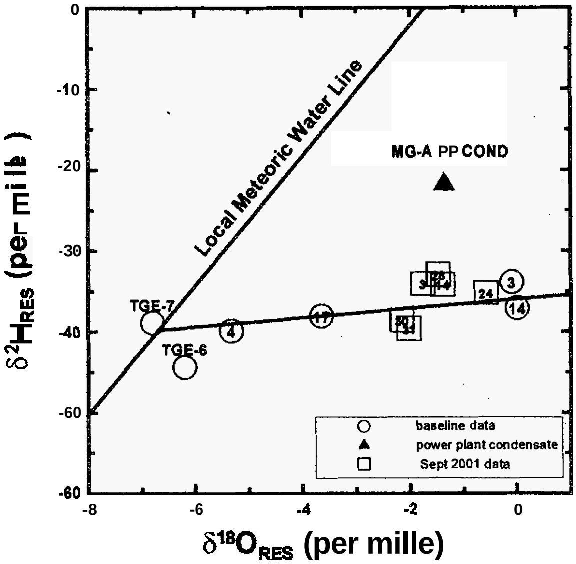

Figure 4. The present isotopic composition of deep wells in Mahanagdong field.

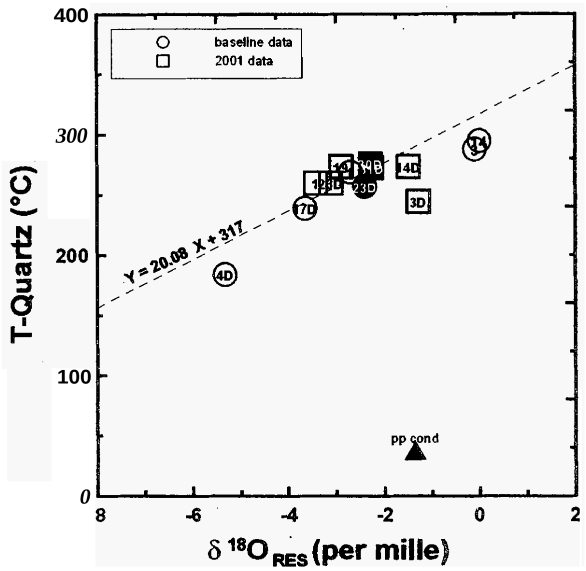

Figure 5. Plot of stable isotope with fluid temperature based on T(Quartz).

evidences of possible condensate returns from well **MG-SD.**

3.3 Inflow of Condensate Fluids

MG-3D's reservoir chloride continued to decline and stabilize at 2500 mg/kg in 2001 compared to its 4500 mg/kg level in 1999 suggesting that the inflowing fluids have already equilibrated with the geothermal fluids of MG-3D. However, its fluids have still not reached thermal equilibrium as evidenced by the significant decline in its quartz geothermometer from a high of 290°C (1999) down to 245°C (Oct. 2001). The increase in resetvoir sulphate levels from 22-27 mg/kg (Jan 2001) to 35-40 ***mgkg*** (Oct. 2001) and its decline in reservoir calcium and magnesium may prove that these fluids are dilute, sulphate-rich condensate type of fluids (Table 1). Bore output data further show the decline in discharge enthalpy of MG-3D from 1500 kJ/kg in March 2001 to 1420 kJ/kg in June 2001 and the significant increase in waterflow from 49 kg/s to 54 kg/s.

Well MG-14D showed the same effects of possible condensate returns as in well MG-3D as indicated in its continuing decline in chloride concentration from 4700 mg/kg in Oct-2000 to 3400 mg/kg in Oct-2001. However, its stable quartz geothermometer of 275°C implies that the condensate fluids are sufficiently reheated upon reaching the well. It should be noted that the well is the hottest in Mahanagdong, having a quartz geothermometer of 290°C in 1997. Bore output data showed the continuous decline in enthalpy from 2400 kJ/kg (Oct 1999) to 1800 kJ/kg in June 2001. MG-30D and MG-31D exhibited similar declining trends in its reservoir chloride, quartz geothermometer, gas in total discharge and enthalpy that suggest the continuous inflow of liquid recharge into the well.

A comparison of the chemistry of a typical groundwater with that of power plant condensate in Table I shows the earlier to have elevated values of Ca, Mg and SO_4. The values of Ca from wells MG-3D, MG-14D, MG-30D and MG-31D fall between these two kinds of fluids while the values of sulphate from these wells all fall below the sulphate values of the two fluids. The chemistry data therefore is insufficient to pinpoint the kind of fluid inflowing in these wells.

To resolve the issue, water samples were collected from these affected wells last July 2001 and were analyzed for stable isotope. An evaluation of the isotope data was conducted and the results are represented as cross plots in Figures 4 to 7. The power plant condensate has a composition of $\delta^{18}O$ = -1.36 ‰ and δ^2H = -21.82 ‰ (Figure 4) and are more isotopically enriched in δ^2H relative to the production wells. The current plot of data points of wells MG-3D, 14D, 30D and 31D appear to have shifted towards MG-4DA and MG-17D data

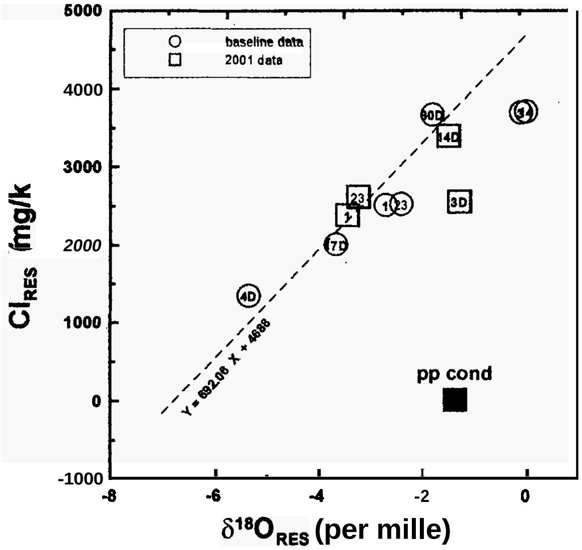

Figure 6. Cross plot of $\delta^{18}O$ and reservoir chloride concentration

points relative to their baseline data points. This implies that these have become more depleted with heavy isotopes due to the diluting effect of mixing with the groundwater type of fluids. The groundwater type fluids down flowing in wells MG-4DA and MG-17D may also be affecting wells MG-3D, MG-14D, MG-30D and MG-31D.

The cross plot of $\delta^{18}O$ vs. T(quartz) and $\delta^{18}O$ vs. Cl_{RES} (Figures 5 and 6) using the same data points likewise show a shift towards of the present data points towards MG-4DA and MG-17D suggesting the mixing with groundwater type of fluids. However, worth noting is the data point of well MG-3D in Figure 6. Well MG-3D present data point shifted away from the baseline regression line towards the power plant condensate data point. The deviation suggests that the discharge fluids of MG-3D may consist of reservoir fluids with a mixture of power plant condensates. This is possible since MG-3D lies nearest to the condensate injection well, MG-9D. However, the general shift of data points towards MG-4DA and MG-17D is an indication that dilute and isotopically depleted waters akin to the groundwaters from the northwest sector are primarily affecting wells MG-3D, MG-14D, MG-30D and MG-31D.

The present distribution of stable isotopes across the Mahanagdong geothermal field is depicted in Figure 7. The present incursion of the cooler fluids into the deep reservoir has been manifested by an increase in indention of the isotopically depleted waters or the increase in area of the -3.0 ‰ and -2.0 ‰ $\delta^{18}O$ contour interval. These waters are coming from the northwest part of the field towards the production area in the south. This type of fluid is suspected to be coursed through the Lower Mahanagdong, Mamban and Ewex faults.

To address the incursion of these cool fluids into the production zone, the initial reservoir management strategy implemented is the transfer of the condensate load from well MG-9D to the off-field reinjection pad, MG-RDIB by the construction of a condensate line. It is envisaged that these condensate fluids further aggravate the inflow of the groundwater type of fluids into the production field which cause the decline in output of the wells. Furthermore, tracer tests will be conducted within the year to fully evaluate the hydrological flow paths of condensates, injected brine and groundwaters into the reservoir.

4.0 CONCLUSIONS

The integration of chemistry and stable isotope data identified the inflow of groundwaters in wells MG-14D, MG-30D, MG-31D and MG-23D as the cause of the primary decline in chemical and physical parameters. This is contrary to the initial findings indicating power plant condensate as the main cause. However, the shift of MG-3D $\delta^{18}O$ trend towards the power plant signature implies that this well may be affected by the inflow of power plant condensate. In general, the commercial exploitation of Mahanagdong starting in 1997 has induced the migration of groundwater from the northwestern periphery towards the production sector of the field. This is manifested by the negative shift in the stable isotopic composition and the corresponding changes in liquid chemistry of production wells close to the said area.

REFERENCES

Alvis-Isidro, R.R., Solaña, R.R., D'Amore, F., Nuti, S. and Gonfiantini, R. (1993). Hydrology of the Greater Tongonan geothermal field as deduced from geochemical and isotopic data. Geothermics 22, 435-449.

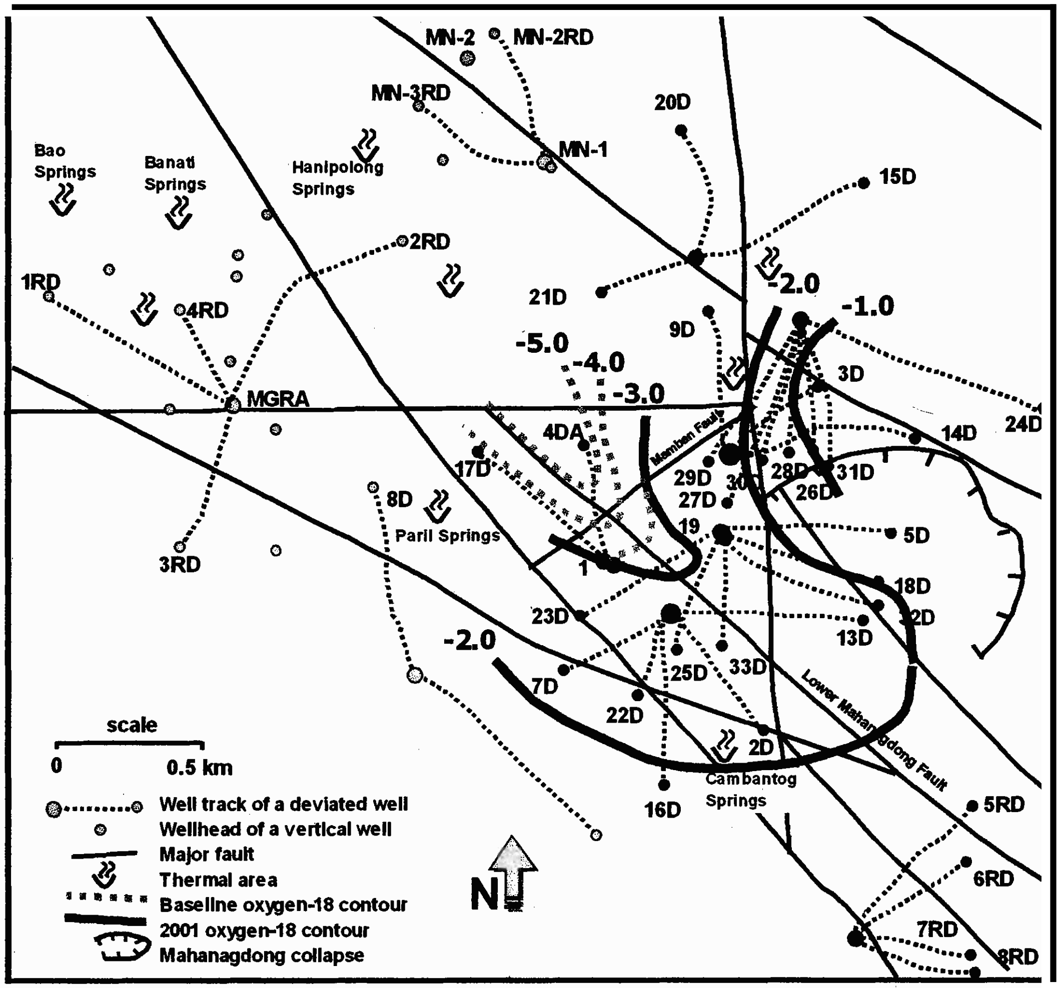

Figure 7. The present $\delta^{18}O$ contour (in per mille VSMOW) of the deep reservoir fluids in Mahanagdong showing increased indentation of isotopically depleted fluids from the northwestern sector (after Salonga and Siega, 1996)

Bolaños, G.T. (1998). Mahanagdong reservoir: Performance for the year 1998. PNOC-EDC unpub. internal report.

Dacillo, D.B. (1999). 1999 annual report; Mahanagdong reservoir chemistry. PNOC-EDC unpub. internal report.

Delfin, F.G., Jr., Barry, B., Dacillo, D.B., Marcelo, E.A. (2001). Analysis and interpretation of ^{125}I tracer test results, Mahanagdong geothermal reservoir, Leyte, Philippines. Paper presented at the IAEA Project Coordinators Meeting (RAS/8/092, INT0060) March 2001, Makati, Philippines.

Herras, E.B. (2000). 2001 annual report – Mahanagdong reservoir geochemistry. PNOC-EDC unpub. internal report.

Hulston, J.R., Stewart, M.K., Glover, R.B., Camales, R.A., Bogie, I.M. and Barnett, P.R. (1982). Stable isotope geochemistry of the Tongonan geothermal system, Leyte, Philippines. Proc. of Pacific Geoth. Conf. 1982 and 4th NZ Geoth. Workshop, Auckland.

Salonga, N.D. and Siega, F.L. (1996). Preliminary report on the stable isotope geochemistry of Mahanagdong geothermal field, Leyte. PNOC-EDC unpub. report.

Seastres, J.S, Jr., Salonga, N.D. and Siega, F.L. (1999). Monitoring the movement of the cooler fluids in the deep geothermal reservoirs of Greater Tongonan geothermal field, Philippines. Proc. IAEA Symposium on Isotope Techniques in Water Resources Development and Management, IAEA SM361/41, Vienna.