Proceedings 20th NZ Geothermal Workshop 1998

APPLICATION OF THE SNHC GAS EQUILIBRIA METHOD IN MONITORING RESERVOIR PROCESSES IN TONGONAN GEOTHERMAL FIELD, PHILIPPINES

N.D. SALONGA[1], D.B. DACILLO[1], F.L. SIEGA[1]
E.V. PARRILLA, Jr. [1] AND F. D'AMORE[2]

[1]PNOC Energy Development Corp., Makati City, Philippines
CNR International Institute for Geothermal Research, Pisa, Italy

Summary: The SNHC gas equilibria method involves three reactions, namely the Fischer-Tropsch (FT), the pyrite-magnetite (HSH), and the pyrite-magnetite-ammonia (SNHC). Solving simultaneously the equilibrium equations of these reactions generates the reservoir temperature (T_{SNHC}), the reservoir steam fraction (y_{SNHC}) and the partial pressure of CO_2 (P_{CO2}). The variation in the trends of the calculated reservoir parameters with time indicates specific physical process. Selected wells in the production sector demonstrated the processes of interplay of feed zone with varying well discharge pressure, the reservoir pressure drawdown, and the mixing of reinjected fluids. On field-wide basis, the contours of these three parameters depicted the temperature, pressure and steam fraction distribution, thereby, delineating the areas affected by reservoir-wide drawdown.

1. INTRODUCTION

Tongonan is an example of a water-dominated geothermal system that has attained full fluid-mineral equilibrium. Application of water geochemistry has been successful during the exploration phase in the 1970's and in monitoring reinjected fluid mixing in production wells in 1988 to the middle 1990's (Lovelock et al., 1982; Alvis-Isidro et al., 1993; Salonga et al., 1997).

However, upon the installation of more power plants in 1997 with a gross capacity of 470 MWe, the water phase in the reservoir fluids decreased as a consequence of reservoir-wide drawdown. The most direct manifestation of this phenomenon is the shift from water-saturated to highly two-phase and steam-dominated well discharges. Reservoir monitoring tools that relied on water geochemistry no longer reflected the reservoir temperatures and processes. This failure led to evaluation and adaptation of alternative geochemical tools, which is based on the gas contents of the fluids.

This paper demonstrates the application of gas equilibria approach in monitoring reservoir physical processes in Tongonan field. It has a specific objective of evaluating the application of the SNHC gas equilibria method, using the reactive gas species of CO_2, H_2, CH_4, H_2S, N, and NH_3.

2. THEORY

The basic assumption in this work, called the SNHC gas equilibria method, is the equilibration of the thermal fluids with the following three reactions:

$$CH_4 + 2\,H_2O = 4\,H_2 + CO_2 \quad (1)$$

$$H_2 + 3/2\,FeS_2 + 2\,H_2O = 3\,H_2S + 1/2Fe_3O_4 \quad (2)$$

$$N_2 + 4\,H_2 + 3/2\,FeS_2 + 2\,H_2O = 3\,H_2S + 2\,NH_3 + 1/2\,Fe_3O_4 \quad (3)$$

This method, as in any other geochemical tools, works best in wells with single feed zone and multiple feed zones but with distinct chemical signature at varying well discharge pressure.

Using the mass action law equation, the equilibrium relations of the above reactions can be expressed in terms of the partial pressure of CO_2 (D'Amore et al., 1987 and 1988):

$$\log P_i = \log (n_i/nCO_2) - \log A_i + \log A_{CO2} + \log P_{CO2} \quad (4)$$

where $(n_i/n\,CO_2)$ is the measured molar concentration of the gas "i" with respect to CO_2. A_i for each gas can be defined as a function of temperature and the in-place steam fraction "y". If y is defined as the fraction of steam present with the liquid in the reservoir, then:

$$A_i = y + (1-y)/B_i \quad \text{at } y>0 \quad (5)$$

If y is defined as the fraction of steam lost from the liquid in the reservoir, then:

$$A_i = 1/[B_i\,(1 + y - y\,B_i)] \quad \text{at } y < 0 \quad (6)$$

B_i is the vapor-liquid distribution coefficient, the ratio of the concentrations of each gas in the vapor and liquid phases. The values of the distribution coefficients are known functions of temperature (Giggenbach, 1980; D'Amore and Truesdell, 1988). Inserting equation (4) for each P_i in the mass action law equations, and using suitable expressions as a function of the absolute temperature (°K) for the

equilibrium constants and the steam pressure (e.g. Giggenbach, 1980; D'Amore and Truesdell, 1988), each gas species can be expressed as molar ratio with respect to CO_2, as follows:

$$\mathbf{HC} = 4 \log (H_2/CO_2) - \log (CH_4/CO_2) = F_1(T) + F_1(T, y) - 4 \log P_{CO2} \quad (7)$$

$$\mathbf{SHC} = 3 \log (H_2S/CO_2) - \log (H_2/CO_2) = F_2(T) + F_2(T, y) - 2 \log P_{CO2} \quad (8)$$

$$\mathbf{SNHC} = 3 \log (H_2S/CO_2) + 2 \log (NH_3/CO_2) - \log (N_2/CO_2) - 4 \log (H_2/CO_2) = F_3(T) + F_3(T, y) \quad (9)$$

where:

$$F_1(T) = 6.69 - 12144.08/T + 4.635 \log T \quad (7.1)$$
$$F_1(T, y) = 4 \log A_{H2} - 3 \log A_{CO2} - \log A_{CH4} \quad (7.2)$$
$$F_2(T) = 17.25 - 10318.15/T - 0.412 \log T \quad (8.1)$$
$$F_2(T, y) = 3 \log A_{H2S} - 2 \log A_{CO2} - \log A_{H2} \quad (8.2)$$
$$F_3(T) = 5.45 - 4{,}918.15/T - 0.412 \log T \quad (9.1)$$
$$F_3(T, y) = 3 \log A_{H2S} + 2 \log A_{NH3} - 4 \log A_{H2} - \log A_{N2} \quad (9.2)$$

The resolution of the above equations is then considered. In each of the expressions from (7) to (9), the left side is made up of known terms produced from the chemical analysis of the *dry* gas. The right side of each equation is a non-linear function of temperature, steam fraction y and of CO_2 partial pressure. The set of three non-linear equations can be used to calculate the temperature (T_{SNHC}), steam fraction (y_{SNHC}) and P_{CO2} values in the reservoir by means of a numerical approach. The computation procedures can be put in a computer program.

3. VALIDATION OF THE CALCULATED SNHC PARAMETERS

The well gas discharge data used in this paper and the corresponding calculated chemical parameters appear in Table 1. The table evidently shows an excellent correlation between T_{SNHC} and T_{quartz} with a mean difference of about ± 2.44% but not with T_{NaKCa} nor with $T_{FT\text{-}HSH}$. In Tongonan geothermal field, T_{quartz} closely approximates the measured downhole temperature of the feed zones; thus, T_{SNHC} may also give close approximation of the reservoir fluid temperature.

The steam fraction, y_{SNHC} is validated with the steam fraction estimated from the FT-HSH method (D'Amore and Truesdell, 1988). Production wells drilled near the center of the resource, have y_{SNHC} close to zero (0) while those well at the peripheral sector of the field in the north and southeast have more negative y_{SNHC} values. The FT-HSH method indicated a wider range of y. It predicted zero to positive y values for wells lying close to the center of the resource and zero to negative y values for wells at the periphery of the field with lower gas level.

There is a fair correlation between the calculated partial pressure of CO_2 based on SNHC and speciation method (Amorsson, et al., 1982). The SNHC method, however, indicated lower P_{CO2} by about 0.93%. All of the wells have present CO_2 partial pressure of less than 1.0 MPa; the calculated P_{CO2} ranges from 0.1 to 0.8 MPa.

4. EVALUATION OF WELL PROCESSES

4.1 Interplay of Feed Zones

Well 108, found in Mahiao sector, has two major feed zones. Based on water and gas chemistry trends (Fig. 1), the feed zone shifts whenever the well is utilized at different well discharge pressure. At high pressure, the condition from 1984 to 1986, the lower zone with discharge enthalpy of 1600 kJ/kg and total discharge chloride of 6000 mg/kg dominated. When the well is utilized at low pressure from 1987 to 1996, the major contributor of the discharge becomes the upper feed zone with discharge enthalpy of 2200 kJ/kg and total discharge chloride of 2500 mg/kg.

The trend of SNHC parameters reflects the same process. From 1984 to 1986 when the discharge pressure is high, the values of the temperature and partial pressure of CO_2 are generally high at 280°C and 0.50 MPa, respectively (Fig. 1). These trends indicate that feed zone shifted to the liquid-rich lower zone. When the well was utilized mostly at fully-open condition or at lower discharge pressure from 1987 to 1996, the general trends of T_{SNHC} and P_{CO2} abruptly shifted to lower values of 270°C and 0.25MPa, respectively, indicating that the cooler, less pressurized, and steam-rich upper feed zone has dominated. The steam fraction (y_{SNHC}) on the other hand, had been higher at about 0%.

In 1994, when the well was again utilized mostly at high discharge pressure, the fluid production shifted back to the lower zone as indicated by the rise in T_{SNHC} and P_{CO2} with a corresponding drop in y_{SNHC}.

4.2 Reservoir-wide Pressure Drawdown

In well 212, the process of pressure drawdown started to manifest towards the end of 1997. Even with similar discharge pressure, there were declines in the reservoir chloride concentration and in T_{Quartz} (Fig. 2), from 10,000 to 4,000 mg/kg and from 280°C to 250°C, respectively. This decline was paralleled by the increase in discharge enthalpy from 1600 to 2700 kJ/kg and by the increase in the total discharge CO_2 from 100 to 250 mmoles/100 moles steam.

During the same period, the general trend of y_{SNHC} is increasing, indicating an increase in the steam present in the local reservoir. The partial pressure of CO_2 on the other hand declined which is attributed to the decline in total reservoir pressure.

Table 1. Gas data in total discharge composition and calculated parameters of Tongonan wells.

WELL	H	CO2td	H2Std	NH3td	H2td	N2td	CH4td	T_{SNHC}	T_{Quartz}	T_{NKC}	T_{FT-HSH}	y_{SNHC}	y_{FT-HSH}	$P_{CO2(SNHC)}$	$P_{CO2(emp)}$
	(kJ/kg)	µmol/mol H_2O						(°C)	(°C)	(°C)	(°C)			(MPa)	(MPa)
103	2151	1178	180	8.7	17.7	3.71	9.77	290	279	285	310	-0.007	-0.001	0.17	0.22
108	2440	6060	302	10.7	40.6	12.21	7.94	265	257	278	325	0.001	0.020	0.17	0.85
109	2790	2553	358	10.6	38.5	6.56	14.53	298	-	-	325	-0.005	0	0.21	-
110	2674	2583	327	10.4	41.8	10.54	5.31	280	-	-	325	0	0.010	0.12	-
209	2304	1650	264	8.5	25.5	13.30	2.56	295	281	287	320	-0.003	0.005	0.15	0.28
212	2297	2558	243	10.1	25.8	8.79	3.64	270	270	274	320	-0.001	0.005	0.11	0.39
213	2048	1200	190	8.0	33.8	61.00	1.95	290	294	284	310	0.005	0.030	0.11	0.25
2R2	1952	2083	156	7.4	23.6	5.90	5.21	265	269	283	300	0	0.010	0.12	0.40
301	2789	3099	209	13.9	26.1	16.74	5.65	267	253	274	315	0	0.007	0.15	0.31
303	1857	2230	116	9.1	10.5	13.20	3.63	270	268	281	300	-0.002	0	0.23	0.47
305	2126	1835	132	8.9	10.7	9.75	3.07	275	273	283	300	-0.004	0	0.21	-
310	1257	614	34	8.5	2.2	5.00	0.99	255	261	286	265	-0.004	-0.001	0.15	-
401	2463	2497	322	11.6	27.7	8.40	3.96	280	280	299	325	-0.004	0	0.12	-
412	2623	3463	271	10.8	33.2	21.12	3.56	274	267	296	320	0.001	0.020	0.15	-
414	2385	2200	194	10.6	9.6	9.36	3.04	300	285	299	315	-0.024	-0.020	0.41	0.40
418	2190	3051	143	11.0	21.3	25.19	6.65	270	271	287	300	0.001	0.010	0.22	-
503	1303	608	41	6.6	2.5	8.91	1.75	290	278	282	270	-0.014	-0.005	0.40	-
509	1222	1622	32	7.3	3.2	11.24	6.08	273	258	270	265	-0.003	0	0.70	0.81
511	1778	2745	152	11.4	17.1	7.72	12.05	275	276	287	300	-0.002	0.001	0.26	0.58
514	1369	921	34	7.1	1.7	2.70	5.01	288	297	290	270	-0.028	-0.005	0.85	0.36
515	1480	1110	70	6.7	5.8	3.74	4.23	280	285	286	285	-0.007	-0.001	0.29	0.34

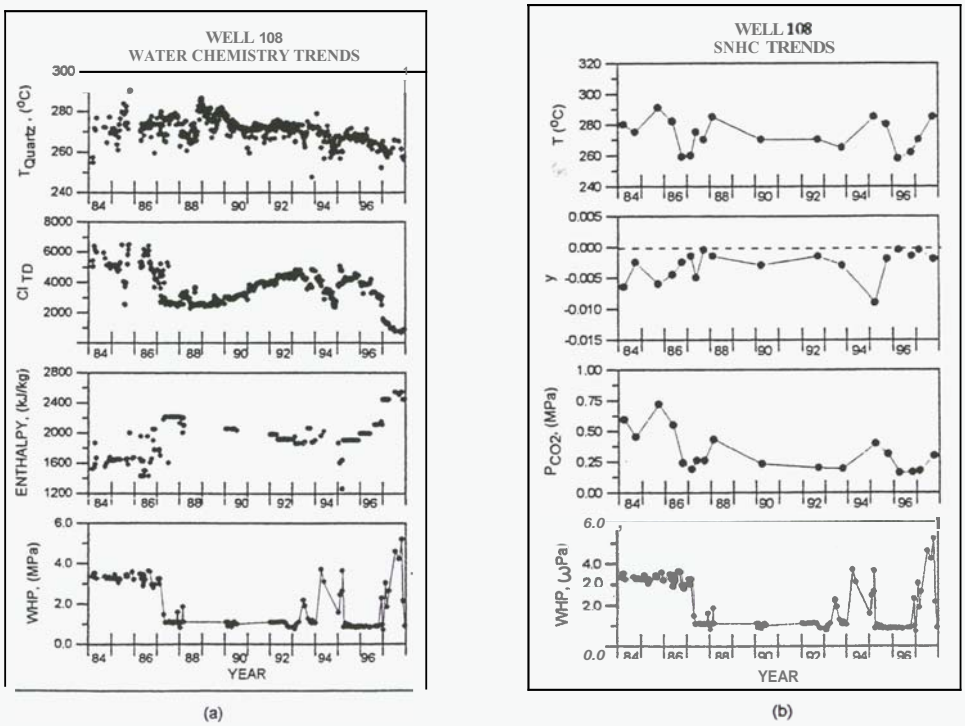

Figure 1. Time series plots of selected chemical parameters (left) and calculated SNHC parameters (right) in Well 108. The interplay of the two feed zones shows the variation of both chemical and SNHC parameters with variation in the well discharge pressure.

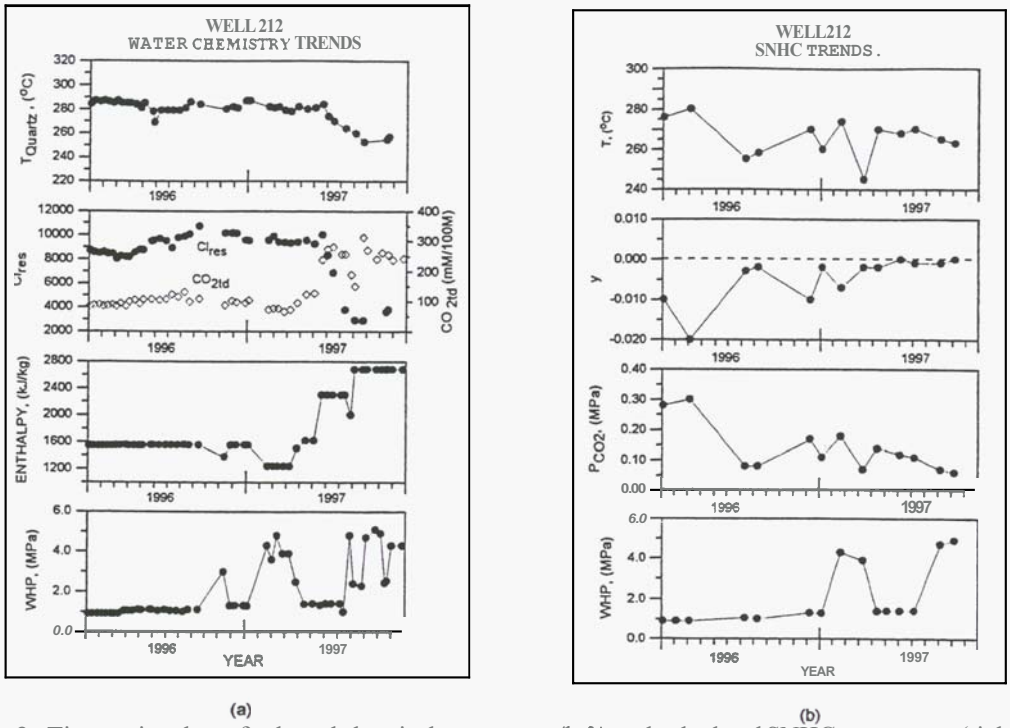

Figure 2. Time series plots of selected chemical parameters (left) and calculated SNHC parameters (right) in Well 212. Reservoir drawdown started to occur in 1997 when $CO2_{td}$ and y_{SNHC} increased, while Cl_{res}, T_{Qtz}, T_{SNHC} and P_{CO2} declined.

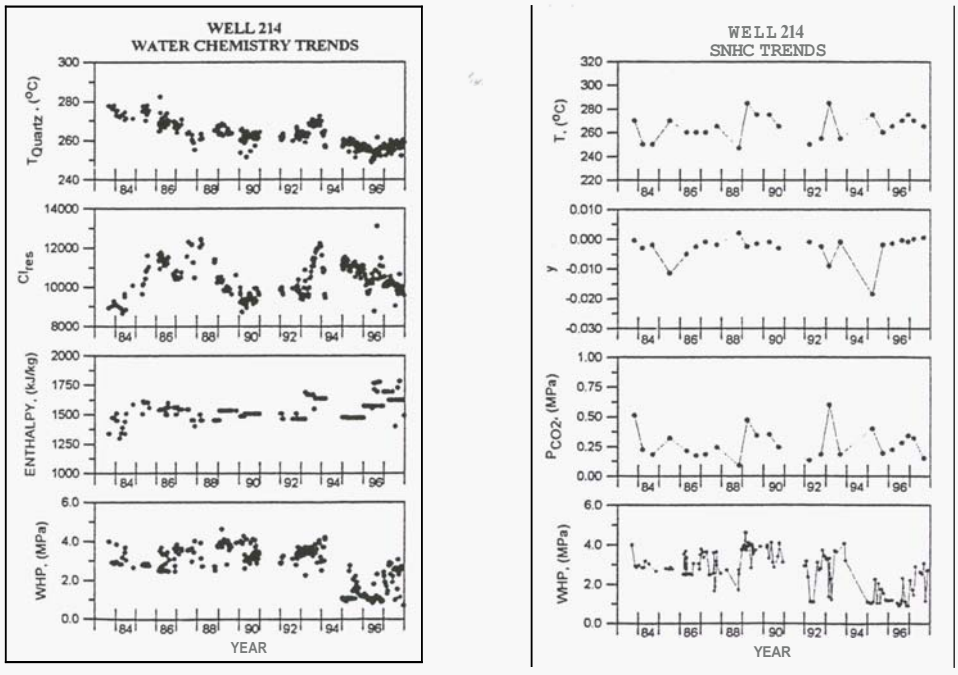

Figure 3. Time series plots of selected chemical parameters (left) and calculated SNHC parameters (right) in Well 214. Mixing of reinjected fluids occurred from 1992 to 1995 when Cl_{res} increased with corresponding decline in T_{Qtz} and y_{SNHC}. The T_{SNHC} and P_{CO2} were relatively stable at 260° C and 0.25 MPa, respectively.

T_{SNHC} during this period is showing very slight gradual decline from 270°C to 260°C.

4.3 Mixing of Reinjected Water

Well 214 of the Sambaloran sector lies near the Mahiao-Sambaloran reinjection sink. After a local drawdown from 1983 to 1988, the well was severely affected by the reinjected fluids from 1989 to 1995 as indicated by the increase in chloride and decline in discharge enthalpy. From 1995 to 1997, the amount of reinjected fluids was reduced which resulted to the recovery of the well from reinjection returns as reflected by the decline in reservoir chloride and corresponding increase in well discharge enthalpy.

In the plot of SNHC parameters, from 1988 to 1995, the values of steam fraction have been declining from 0% until it reached its lowest level of -0.2% in 1995 when the reinjection load in the sector was at its maximum. T_{SNHC} during this period has also been declining from 280°C to 250°C due to the cooling effect of the reinjected fluids. On the other hand, the P_{CO2} parameter has shown periodic fluctuations from 0.10 to 0.50 MPa, which can be an indicator of pressure recovery of the sector.

When the reinjection load was reduced in 1996, the three SNHC parameters have shown increasing trends suggesting Well 214's recovery from reinjected fluids and the onset of the reservoir-wide drawdown.

5. THE PRESENT FIELD-WIDE TRENDS

5.1 T_{SNHC} Isothermal Contour

Figure 4 shows the isothermal contours of the calculated T_{SNHC} across the field. A maximum temperature of 300 °C covers the Upper Mahiao to Sambaloran sector. The T_{SNHC} in this area affirms with the accepted hydrothermal flow model of the field, which identified the centre of the field at the Upper Mahiao area. (Lovelock et al., 1982; Salonga et al., 1997).

Broad 270-290 °C isothermal contours extend from the north to the southeast. This declining temperature trend from the Mahiao sector to the Malitbog sector is interpreted to indicate the lateral flow of the geothermal fluids. There is also a presence of relatively low temperature fluids in the southwestern side of the field. With temperatures of less than 260°C, these cooler fluids are interpreted as reinjected waters spreading from the reinjection sink of Mahiao-Sambaloran sectors.

5.2 Distribution of CO_2 Partial Pressure

The contour map of the calculated CO_2 partial pressure (Fig. 5) shows that the area with the most depleted pressure of around 0.10 MPa lies in the hottest area of Mahiao sector. P_{CO2} progressively increases from 0.10 to 0.80 MPa towards the southeast and peripheral areas. This trend is the inverse of isothermal trend, and therefore, the calculated P_{CO2} of the SNHC method must not be viewed as directly related to reservoir temperature. The calculated PCO_2 field-wide trend is rather related to total pressure of the reservoir based on actual downhole surveys (Salonga et al., 1997). Therefore, the area with depressed P_{CO2} is interpreted to be the area severely affected by reservoir drawdown.

5.3 Reservoir Steam Fraction (y) Contour

The contour map of the calculated reservoir steam fraction in Figure 6 shows that the whole field has a generally uniform y value equal to zero at present. The most obvious implication of this map is the presence of a dominantly liquid reservoir feeding the production wells despite the present occurrence of the reservoir-wide pressure drawdown. Relative to the natural state of the Tongonan reservoir, (Salonga et al., 1997), the whole field has already substantial gain in steam fraction. This may indicate two processes. First is the horizontal expansion of the steam-rich fluids from the Mahiao sector to the Malitbog sector. Second is the vertical expansion of the steam-zone in the entire field as a consequence of pressure drawdown.

6. CONCLUSIONS

The SNHC gas equilibria method used three reaction involving the six reactive gas species of CO_2, H_2S, H_2, N_2, CH_4 and NH_3. Numerical calculations generated three reservoir parameters, namely, the fluid temperature, steam fraction and partial pressure of CO_2.

The calculated parameters vary according to the dominant process in discharging well. The variation of these parameters with varying well discharge pressure suggests shift in producing zones within the well. The simultaneous decline in all of the three SNHC parameters suggests mixing of the injected fluids, while the decline in T_{SNHC} and P_{CO2} with corresponding increase in y_{SNHC} indicate pressure drawdown.

The contour maps showing the distribution of the three SNHC parameters showed that almost the entire Tongonan field is affected by the pressure drawdown. The maps also identified an area close to the Mahiao-Sambaloran reinjection sink, affected by the reinjected fluid invasion.

REFERENCES

Alvis-Isidro, R.R., Solana, R.R., D'Amore, and Gonfiantini, R. (1993). Hydrology of the Greater Tongonan geothermal system, Philippines. *Geothermics,* Vol. 22, No. 516, pp. 435-449.

Arnorrson, S., Sigursson S. and Svavarsson, H. (1982). The chemistry of geothermal waters in Iceland. I. Calculations of aqueous speciation from 0'

to 370° C. *Geochim. et Cosmochi. Acta* vol. 46, pp. 1513-1532. Pergamon Press, USA.

D'Amore, F. and Truesdell, A.H., (1985). Calculation of geothermal reservoir temperature and steam fractions from gas compositions. *Geoth. Res. Coun. Trans.*, vol. 9, pp. 305-310.

D'Amore, F., Fancelli, R., Saracco, L. and Truesdell, A.H. (1987). Gas geothermometry based on CO content. Application in Italian geothermal fields. *Proc. 13th Workshop on Geoth. Res. Eng'g.* Stanford University. vol. 13, pp. 247-252

D'Amore, F. and Truesdell, A.H. (1988). A review of equilibrium constants for gaseous species of geothermal interest. *Sci. Geol.* Bull. vol. 41. pp. 309-332

Giggenbach, W.F. (1980). Geothermal gas equilibria. *Geochim. et Cosmochi. Acta,* vol. 44, pp. 2021-2032

Lovelock, B.B., Cope, D.M. and Baltasar, A.S.J., (1982). A hydrological model of the Tongonan geothermal field. *Proc. Pacific Science Con.,* Auckland

Salonga, N.D. and Auman, R.O. (1997). Gas equilibria in Tongonan, Mahanagdong, and Alto Peak geothermal fields, Leyte, Philippines. *Proc. 18th PNOC-EDC Geoth. Con.* pp. 156-167.

Salonga, N.D., Auman, R.O., Alincastre, R.S., Siega, F.L., Pa-a, J.E. and Bolanos, G.T., (1997). The geochemical model of Tongonan geothermal field prior to full commisioning of 450 MWe power plants. *Proc. 18th PNOC-EDC Geoth. Con.* pp. 172-181.

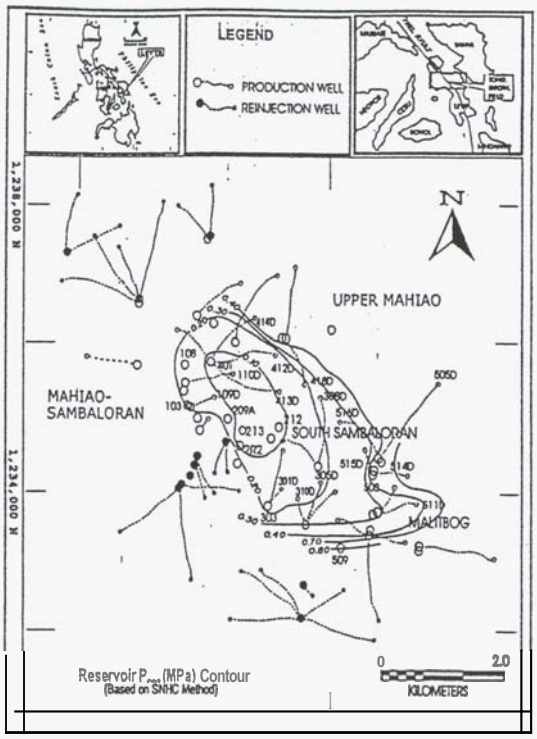

Figure 5. P_{CO2} contour map based on T_{SNHC}

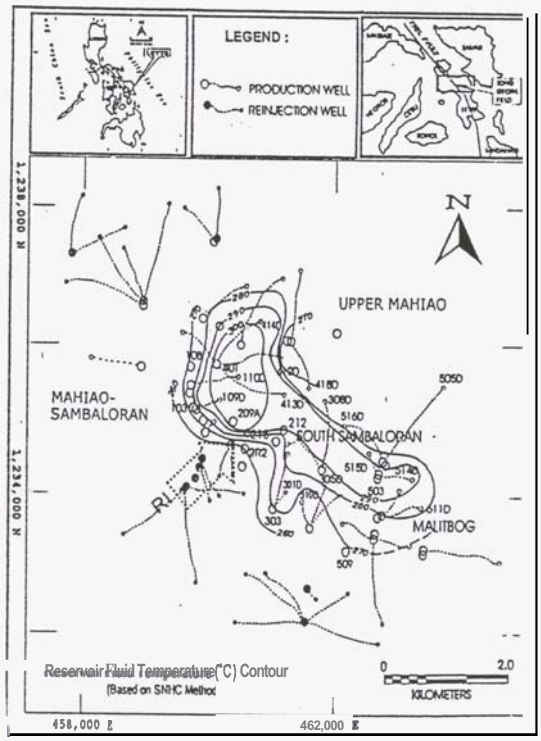

Figure 4. Isothermal map of T_{SNHC}

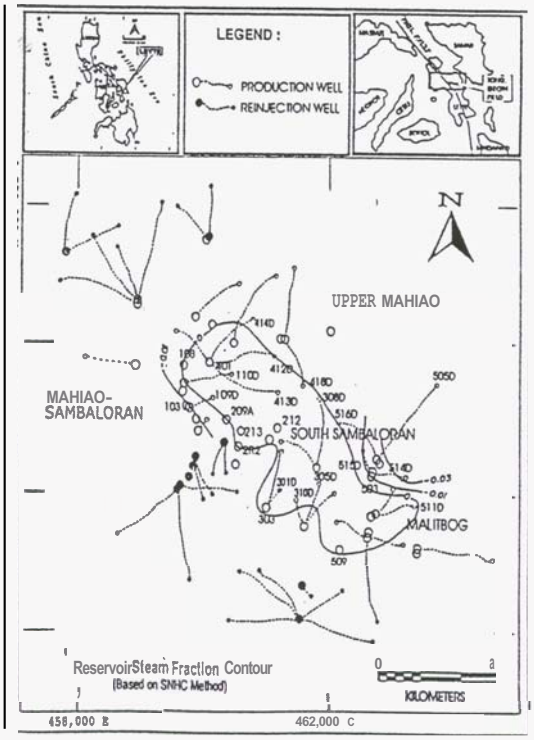

Figure 6. Contour map of Y_{SNHC}