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

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ABSTRACT

The novel gas equilibrium reaction (SNHC) is introduced as a method to calculate reservoir parameters such as temperature, steam fraction and CO_2 *partial pressure. The new approach incorporates* NH_3 *and* N_2 *as an extension of the FT-HSH gas equilibria. The applicability of the method in monitoring reservoir processes in Tongonan geothermal field is evaluated using wells that have been established to have undergone processes such as reinjection returns, pressure drawdown and interplay of feed zones. Wells with various range in enthalpy representing the different fluid discharge characteristics from all the sectors in Tongonan were also evaluated.*

Initial evaluation shows that the reservoir processes in each subject wells suggested by the SNHC method is fairly consistent with processes established by the conventional water and gas chemistry monitoring tools such as T_{SiO2}, Cl_{res}, *and* CO_{2TD} *trends. However, discrepancies in calculated temperature and* P_{CO2} *values are observed in wells 105D and* ***501*** *in the Mahiao and Malitbog sector respectively. These wells are observed to be discharging highly degassed waters with reservoir steam paction of about -0.3. Temperature and* P_{CO2}*-difference obtained are >320°C and >±10% respectively.*

1.0 INTRODUCTION

The Tongonan geothermal field, composed of five sectors namely Upper Mahiao, Mahiao, Sambaloran, South Sambaloran, and Malitbog, lies in the northwestern part of Leyte island (Fig. 1). Forty-nine production wells supply steam to three power plants. Separated brine and condensate are injected back to the reservoir through 27 injection wells located in the periphery of the outflow regions. Eight of these wells comprise the injection sink in the Mahiao–Sambaloran sector, eleven are in Upper Mahiao, and the remaining eight in the Malitbog area.

The total generating capacity of the three power plants is 468 MWe. This huge production of power entails massive extraction of geothermal fluids. During this commercial operation, geochemical tools should be accessible to properly monitor the reservoir, hence provide better management of the geothermal resource. One such tool is SNHC gas equilibria method developed by D' Amore (1997) uses as raw data the composition of only the vapor-phase species. Outrightly, one advantage that can be pointed out is the possibility of its application in vapor-dominated systems or in wells with only vapor-phase discharge. The tool utilizes the equilibrium reactions of CO_2, H_2S, NH_3, N_2, H_2, and CH_4 to calculate the deep temperature, steam fraction, and partial pressure of CO_2 in the reservoir. The graph of these computed parameters with time will give trends reflecting the physical process. It is the objective of this paper to evaluate the consistency of the trends generated using SNHC method with the trends using water chemistry and CO_{2TD}.

The wells used in the evaluation of the method are: 105D and 108 in Mahiao, and 212 in Sambaloran, 303 in South Sambaloran, 406 in Upper Mahiao, and 501 in Malitbog. The data used from these six wells are with the period January 1995 to December 1997.

Two significant reservoir processes have been identified corresponding the above time range of the collected data (Salonga, 1997). The first is reinjection fluid mixing in the Mahiao and Sambaloran

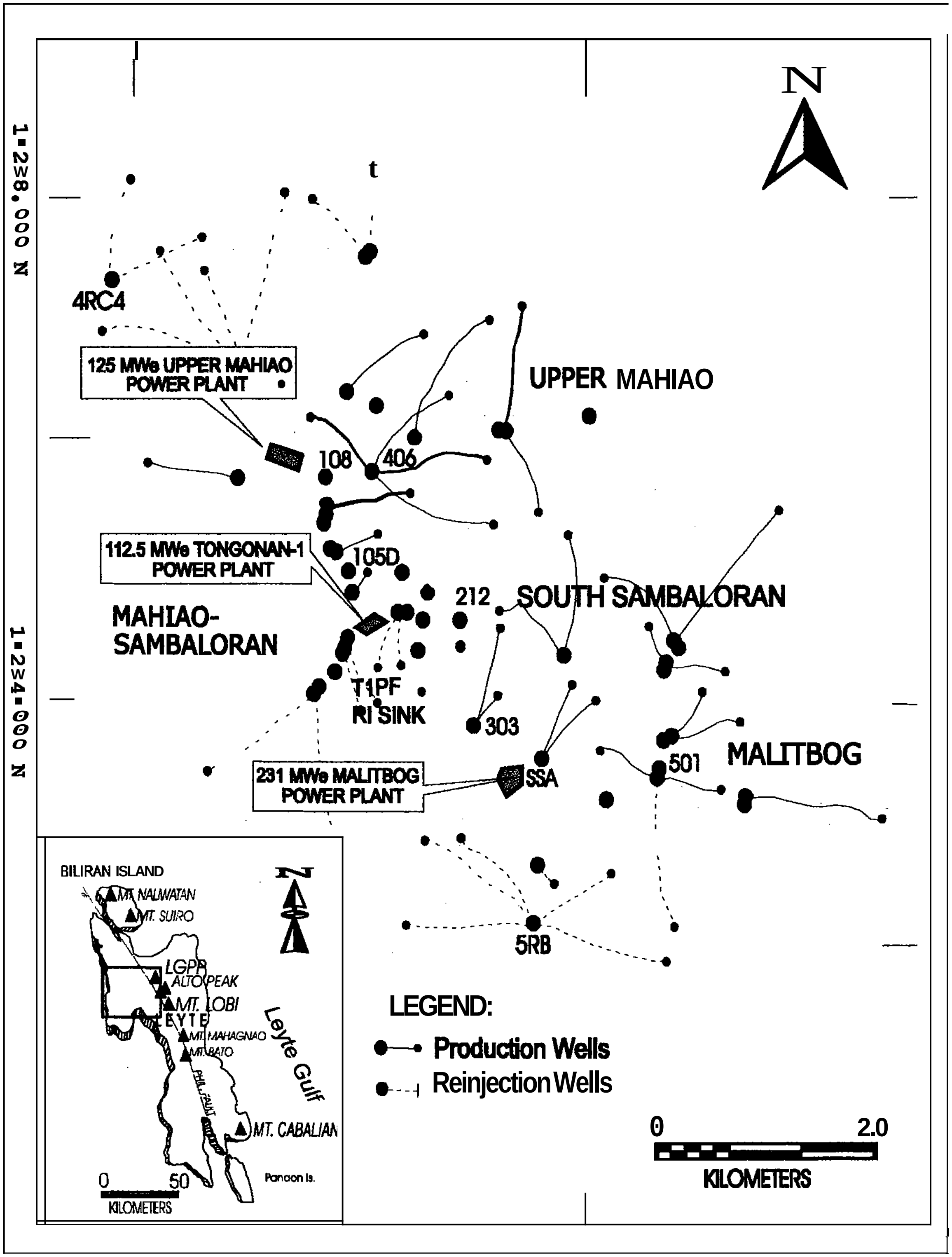

Figure 1. Map of Tongonan Geothermal Field showing the location of the production and reinjection wells and existing power plants.

sectors since 1994. The sector recovered from reinjection fluids when injection load in Sambaloran was reduced from 140 to 90 kg/s Starting September 1995. Towards the middle part of 1997 another process dominated which is pressure drawdown. In Sambaloran wells, the discharge enthalpy and CO_2 increased paralleled with the decline in T_{SiO2} and Cl_{res} which altogether *suggest* reservoir-wide pressure drawdown. This process affected also part of the South-Sambaloran sector. In well 108, an interplay of feed zones was observed.

2.0 METHOD DESCRIPTION

The SNHC tool of D'Amore (1997) uses the analyses of six gas parameters at the point of discharge – CO_2, H_2S, NH_3, N_2, and CH_4. These raw data are used to calculate the reservoir temperature, steam fiaction, and partial pressure of CO_2 at equilibrium conditions wherein these species have reacted or formed.

The essential chemical reactions from which the method are based, are:

$$CH_4 + 2 H_2O = 4 H_2 + CO_2 \quad (1)$$
$$H_2 + {}^3/_2 FeS_2 + 2 H_2O = 3 H_2S + ½ Fe_3O_4 \quad (2)$$
$$N_2 + 4 H_2 + {}^3/_2 FeS_2 + 2 H_2O = 3 H_2S + ½ Fe_3O_4 + 2 NH_3 \quad (3)$$

Using the law of mass action and the equation at equilibrium condition involving the partial pressure of each reacting component, the following relationships can be derived. The chemical parameters involved are in molar ratios with respect to CO_2 instead of H_2O.

$$4 \log (H_2/CO_2) - \log (CH_4/CO_2) = HC = f1(T) + f2(T,y) - 4 \log P_{CO2} \quad (4)$$
$$f1(T) = 6.69\text{-}12144.08/T + 4.635 \log T \quad (5)$$
$$f1(T,y) = 4 \log A_{H2} - 3 \log A_{CO2} - \log A_{ch4} \quad (6)$$

$$3 \log (H_2S/CO_2) - \log (H_2/CO_2) = SHC = f2(T) + f2(T,y) - 2 \log P_{CO2} \quad (7)$$
$$f2(T) = 17.25 - 10318.15/T - 0.412 \log T \quad (8)$$
$$f2(T,y) = 3 \log A_{H2S} - 2 \log A_{CO2} - \log A_{H2} \quad (9)$$

$$3 \log(H_2S/CO_2) + 2 \log(NH_3/CO_2) - \log(N_2/CO_2) - 4 \log(H_2/CO_2) = SNHC = f3(T) + f3(T,y) \quad (10)$$
$$f3(T) = 5.45 - 4918.15/T - 0.412 \log T \quad (11)$$
$$f3(T,y) = 3 \log A_{H2S} + 2 \log A_{NH3} - 4 \log A_{H2} - \log A_{N2} \quad (12)$$

HC, SHC, and SNHC are the names of the geothermometric functions corresponding the three chemical reactions. The letters represent the parhcipating gases. The expression $fn(T)$ is the equation for the equilibrium constant (commonly denoted as Keq) as a function of the absolute temperature. The second function $fn(T,y)$ involves the steam fraction, y, and the distribution coefficient, Bi, a known function of temperature. The in-place steam fiaction can assume a positive or a negative value. If the steam is present in phase equilibrium with the liquid in the reservoir, y is positive. The expression *Ai* would be equal to $[y + (I\text{-}y)/Bi]$. If the steam is lost through open channels before the fluid reaches the wellhead, y is negative. The expression *Ai* would then be equal to $[Bi\ (1 + y - y\,Bi]^{-1}$.

The left sides of the above equations are measurable chemical parameters while the right sides are sets of non-linear functions of temperature, steam fiaction, and partial pressure of CO_2. These physical parameters are computed through numerical method of convergence of the two P_{CO2} values. The values of T and its corresponding y are initially assumed in equation 10. By iterative procedure, T and y would reach their final values when the difference of P_{CO2} values in equations 4 and 7 are within the accepted range. The authors of this paper used P_{CO2} difference limit within ± 5% instead of the suggested 20% (D'Amore, 1997) to reduce the uncertainty range in the computed parameters.

The following limitations and assumptions (D'Amore, 1997) are accounted in using this SNHC method.

1. The chemical reaction must exist and bave reached thermodynamic equilibrium.
2. All chemical species considered must be in both chemical and phase equilibrium.
3. Some steam is considered present or irreversibly lost in phase equilibrium with the liquid water in the reservoir.
4. Fluid at wellhead can consist of fluid mixtures from various sources with different chemical and physical properties. What is obtained through the application of this method is an integrated value of temperature, steam fraction, and partial pressure of CO_2.
5. There is no re-equilibration of the chemical species from the reservoir source to the wellhead
6. The method of convergence is applied considering very little saline waters.

3.0 DATA EVALUATION

3.1 Reinjection Fluid Mixing

Well 105

This well located in the Mahiao sector, is relatively near the Mahiao-Sambaloran reinjection sink. The in-place reservoir of the well is mixed with a relatively big amount of reinjection fluids since 1994 as indicated by (1) the decline in discharge enthalpy from 1200 to 1000 kJ/kg, (2) the continual rise in Cl_{res} (Fig. 2).

Steam fraction (y) in the SNHC trends (Fig 3) reflects very degassed well reservoir with steam loss ≥ 30%. T & P_{CO2} trends are erratic since P_{CO2} difference (δP_{CO2}) is beyond the ± 5% accepted range. SNHC equilibria do not seem to be applicable to highly degassed reservoir with steam loss greater than 30%

Well 212

This is one of the wells in Sambaloran experiencing reinjection fluid mixing which has been the dominant process since late 1980. Indications of this process (Fig. 4) from Jan-95 to mid-96 are the decrease in T_{SiO2} and the increase in Cl_{res}. In mid-1996, the well started to show recovery from reinjection return when the injection load in Sambaloran was reduced starting November 1995. This is shown by increase in CO_{2td} and decrease in Cl_{res} .

In the SNHC trends (Fig. 5), the reinjection fluid mixing is indicated by the decline in T , y, and P_{CO2} from Jan-95 to mid-96. The recovery from reinjection returns is reflected by the increase in T and P_{CO2} from Jul-96 to Jul-97. The sudden drop in T and P_{CO2} trends during the period of Mar-May 1997 is attributed to change in well utilization.

3.2 Pressure Drawdown

Well 212

In mid-1997, the well started to display the effects of drawdown which has *already* propagated in the Tongonan reservoir. In water chemistry trends (Fig. 4), Cl_{res} and T_{SiO2} declined while CO_{2td} and H_{td} increased.

During this period in the gas equilibria trends, it can be noted that while T and P_{CO2} is showing declining response, the y is quite stable and remained within 0 value (Fig. 5). This trend in y might be an indication that the high enthalpy discharge of the well is in equilibrium with a huge amount of its liquid source, thus the discharge is comparatively nil ($y=0$).

Well I08

In 1997, the water chemistry of the well (Fig. 6, p. 6) displayed the effects of drawdown which is already experienced in the Tongonan reservoir. This process seems to be occurring despite changes in bore opening. During this period, the T and P_{CO2} trends are continuously increasing while y remained at 0 value (Fig. 7, p. 6).

3.3 Interplay of **Feed** Zones

Well 108

The well has a shallow feed zone with relatively dilute and lower temperature water. This fluid has also lower CO_{2td} compared to that coming from the deeper feed zone. The shallow zone normally dominates at throttled condition indicated by the decrease in Cl_{res} by ~ **1000** mg/kg and T_{SiO2} by –10 °C as seen on Jan-Apr 1995 when the well was used at a smaller opening (Fig. 6). When the well was used at a bigger opening, localized drawdown was initially the dominant reservoir process. However, at prolonged open condition, well production shifted to the shallow zone (dilute fluids). This can be seen in the 1996 trend wherein the T, y, and P_{CO2} (Fig. 7) are continuously decreasing.

3.4 High Enthalpy Well

Well 406

The two sets of trends showed the same response as wellhead opening is changed from full-open to throttled condition. This can be seen in figures 8 and 9 from February to April 1997.

In the throttled opening starting Mar-1997, Cl_{res} slightly increased, CO2td decreased, and T_{SiO2} was quite stable. This is interpreted to be near wellbore boiling. The SNHC gas equilibria trends however, did not reflect the process as showed by the decreasing T and P_{CO2} while y slightly increased above zero value. Operating the well at different opening, thereafter showed only an increase in CO_{2td} and decrease in Cl_{res} which indicate that the steam zone has expanded and that boiling is occurring farther down the wellbore. This is consistent with the field-wide drawdown experienced in the reservoir. This maybe is reflected in the slight increase in T, y, and P_{CO2}.

For the over-all trend of water chemistry (1995-1997), the decline in T_{SiO2} and Cl_{res} and the increase in CO_{2td} indicates pressure drawdown. The corresponding trends though in T, y, and P_{CO2} are relatively stable.

3.5 Medium Enthalpy Well

Well 303

Water chemistry shows stable trends (Fig 10). The stability of the well condition is also reflected in the SNHC gas equilibria trends (Fig. 11).

3.6 Low Enthalpy Well

Well 501

Well 501 in the Malitbog sector discharges degassed fluids (CO_{2td} < 100 mmol/100mol, Baseline chemistry) since it is located in the outflow region of the Tongonan geothermal system. Intermittent use of the well did not show changes in CO_{2td} and water chemistry (Fig 12).

The gas equilibria gave very high T values > 320 "C (Fig 13) as compared to T_{SiO2} – 280 "C. T and P_{CO2} trends do not reflect the real deep reservoir condition since δP_{CO2} is not within ± 5%. This is the same case in well 105D. Steam fraction trend indicates steam loss greater than 30%.

4.0 CONCLUSION

The SNHC trends have shown consistency in reflecting three physical processes already established by water chemistry and CO_{2td} trends. The processes are ***mixing with reinjection returns, pressure drawdown,*** and ***interplay of feed zones.***

Mixing with reinjection fluids was shown in well 212 by the declining trend in T, *y*, and P_{CO2}. Though the T and P_{CO2} trends in well 105 were wildly variable, *y* indicated that the well reservoir is highly degassed.

Pressure drawdown was reflected in wells 212 with the decline in T and P_{CO2} and with very slight increase (almost stable at 0) in *y*. Moreover, the observed pressure drawdown indicated by water chemistry in well 108 showed opposite trends.

Interplay of feed zones was observed in well 108 with the deeper zone dominating on full-open condition while the shallow zone at throttled wellhead opening.

In well 406 with high enthalpy discharge, the trends were not quite consistent with the process indicated by water chemistry and CO_{2td} trends. In well 303 with medium enthalpy discharge, the method though not conclusive seems applicable.

The method however, is not applicable to highly degassed wells. This as its limitation was proven with well 105D having infestation of reinjection fluids and with well 501 located in the outflow region.

5.0 REFERENCES

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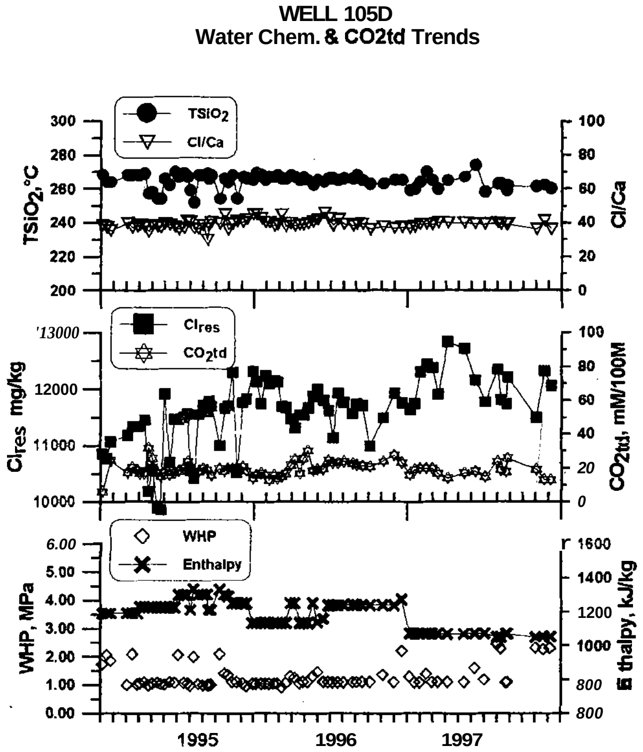
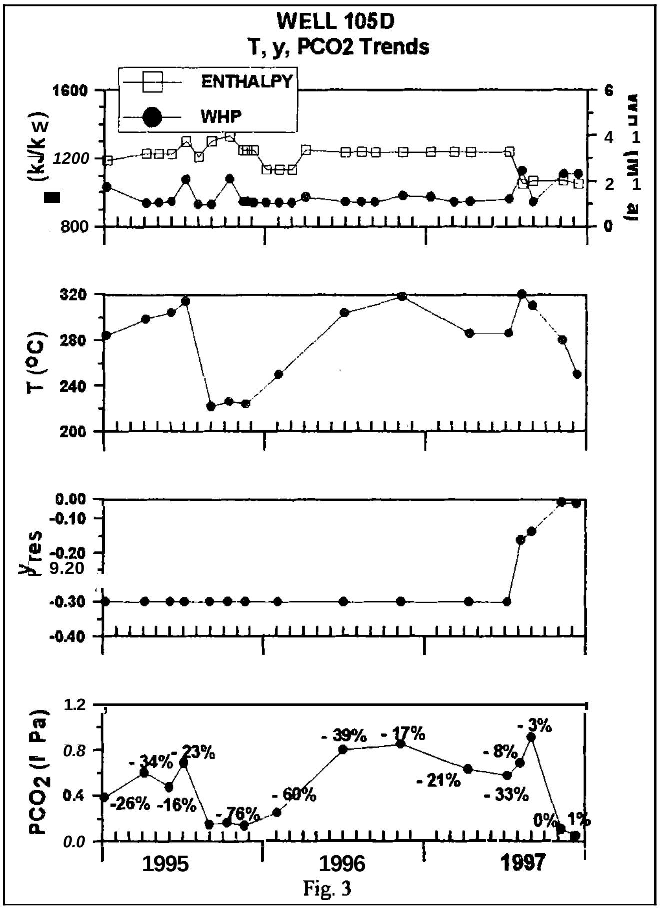

WELL 105D
Water Chem. & CO2td Trends
TSiO2
Cl/Ca
TSiO2, °C
Cl/Ca
Clres
CO2td
Clres mg/kg
CO2td, mM/100M
WHP
Enthalpy
WHP, MPa
Enthalpy, kJ/kg
1995
1996
1997

Fig. 2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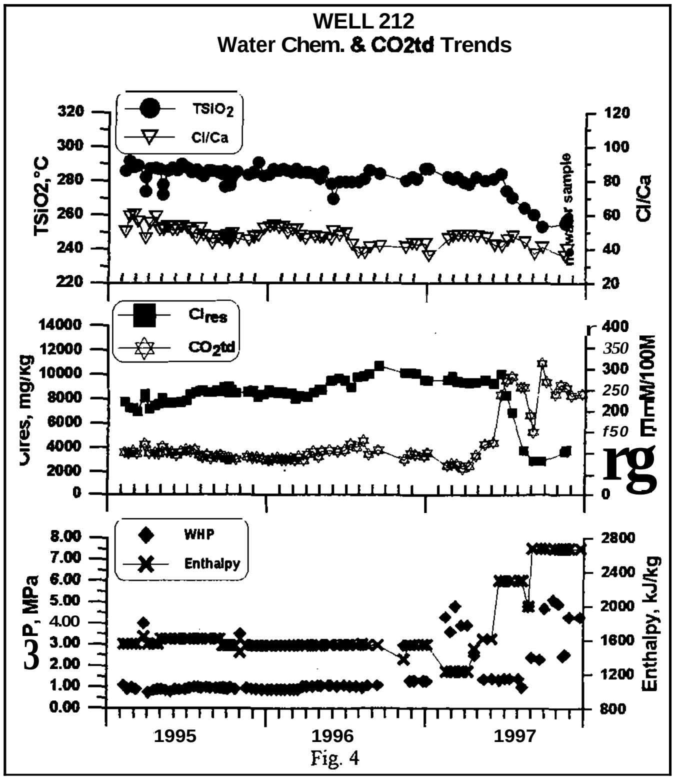
T, y, PCO2 Trends
ENTHALPY
WHP
(kJ/kg)
T (°C)
yres
PCO2 (MPa)
- 34%
- 23%
-26%
-16%
- 76%
- 60%
- 39%
- 17%
- 21%
- 8%
- 33%
- 3%
0%
1%
1995
1996
1997

Fig. 3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Water Chem. & CO2td Trends
TSiO2
Cl/Ca
TSiO2, °C
Cl/Ca
no water sample
Cl res
CO2td
Clres, mg/kg
mM/100M
WHP
Enthalpy
WHP, MPa
Enthalpy, kJ/kg
1995
1996
1997

Fig. 4

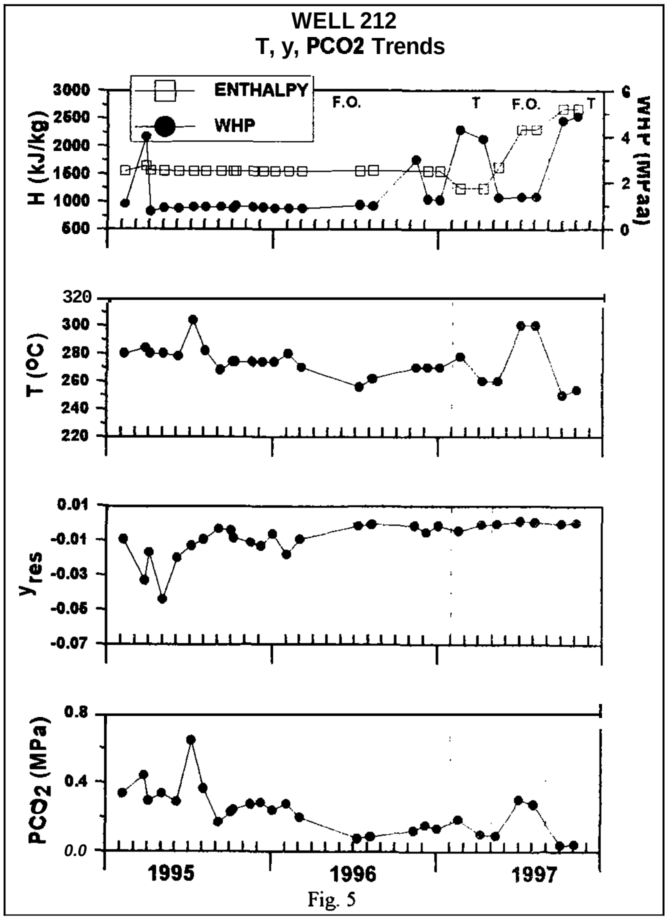

WELL 212
T, y, PCO2 Trends
ENTHALPY
WHP
F.O.
T
F.O.
T
H (kJ/kg)
WHP (MPa)
T (°C)
y res
PCO2 (MPa)
1995
1996
1997

Fig. 5

WELL 108
Water Chem. & CO2td Trends

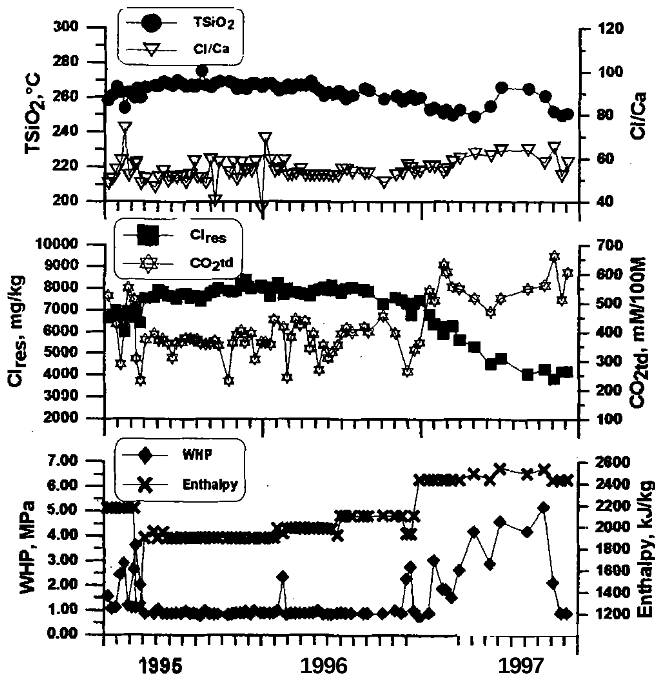


Fig. 6

WELL 108
T, y, PCO2 Trends

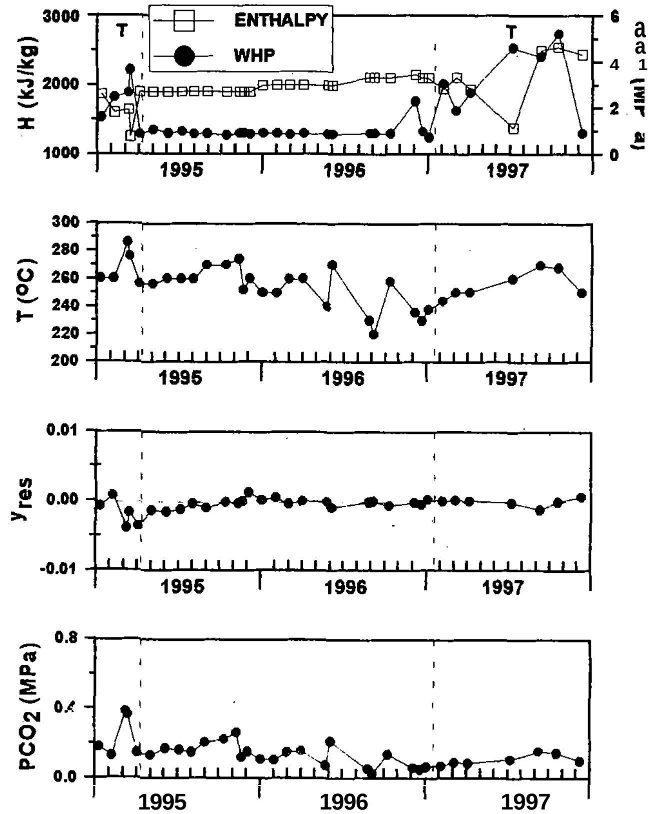
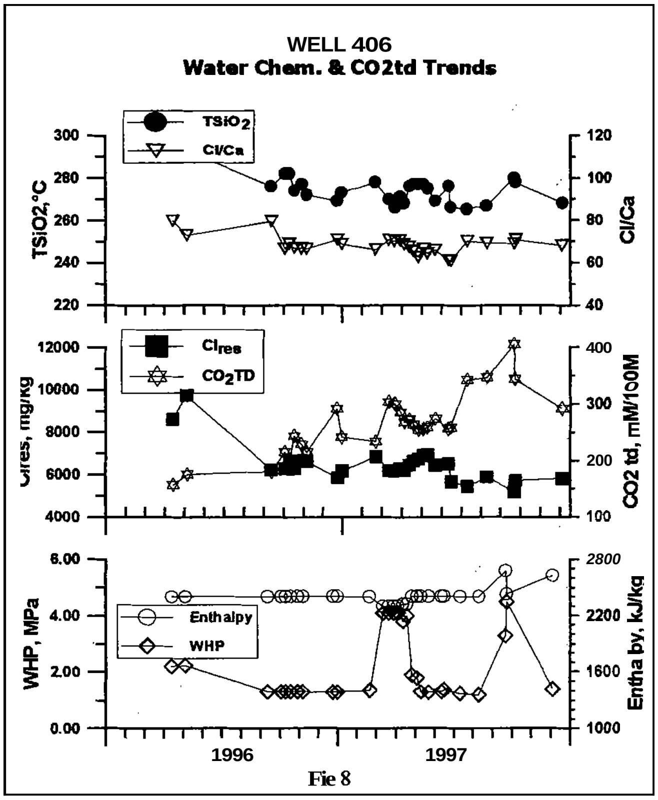
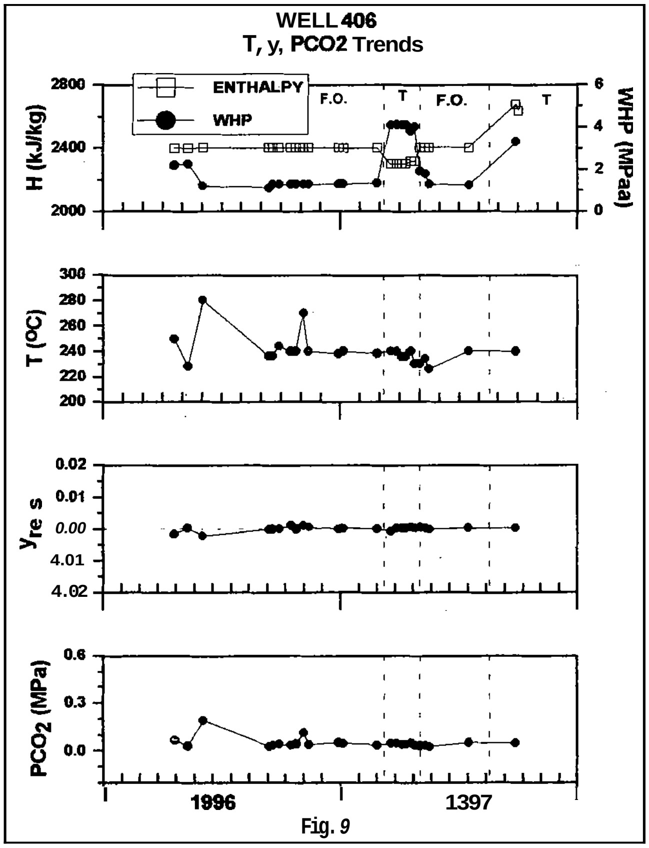


Fig. 7


WELL 406
Water Chem. & CO2td Trends
TSiO2
Cl/Ca
TSiO2,°C
Cl/Ca
300
280
260
240
220
120
100
80
60
40
Clres
CO2TD
Clres, mg/kg
CO2 td, mM/100M
12000
10000
8000
6000
4000
400
300
200
100
Enthalpy
WHP
WHP, MPa
Entha by, kJ/kg
6.00
4.00
2.00
0.00
2800
2200
1600
1000
1996
1997

Fie 8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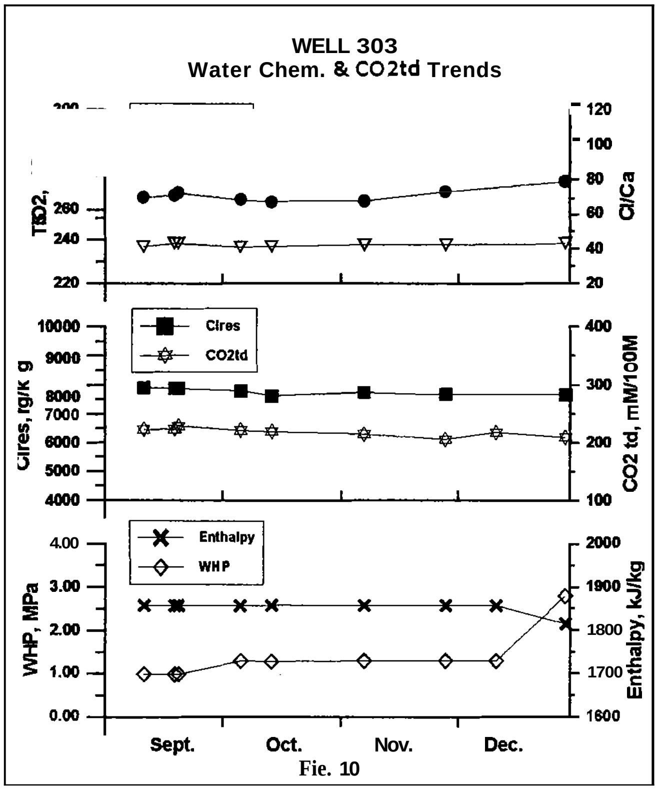
T, y, PCO2 Trends
ENTHALPY
WHP
F.O.
T
F.O.
T
H (kJ/kg)
WHP (MPaa)
2800
2400
2000
6
4
2
0
T (ºC)
300
280
260
240
220
200
Yre s
0.02
0.01
0.00
4.01
4.02
PCO2 (MPa)
0.6
0.3
0.0
1996
1397

Fig. 9


WELL 303
Water Chem. & CO2td Trends
TSiO2,
Cl/Ca
220
240
260
20
40
60
80
100
120
Clres
CO2td
Clres, mg/kg
CO2 td, mM/100M
4000
5000
6000
7000
8000
9000
10000
100
200
300
400
Enthalpy
WHP
WHP, MPa
Enthalpy, kJ/kg
0.00
1.00
2.00
3.00
4.00
1600
1700
1800
1900
2000
Sept.
Oct.
Nov.
Dec.

Fie. 10

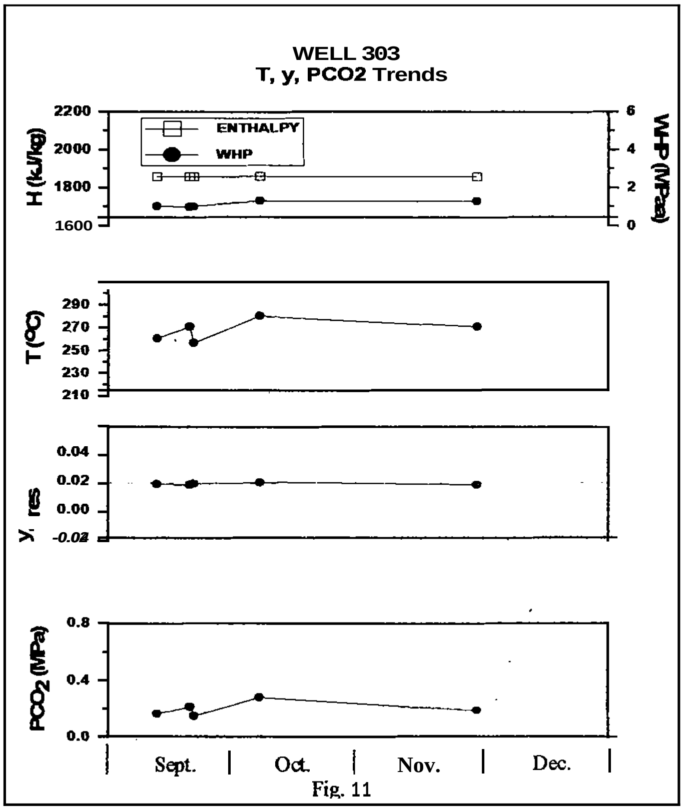

WELL 303
T, y, PCO2 Trends
H (kJ/kg)
WHP (MPa)
ENTHALPY
WHP
1600
1800
2000
2200
0
2
4
6
T (°C)
210
230
250
270
290
y, res
-0.02
0.00
0.02
0.04
PCO2 (MPa)
0.0
0.4
0.8
Sept.
Oct.
Nov.
Dec.

Fig. 11

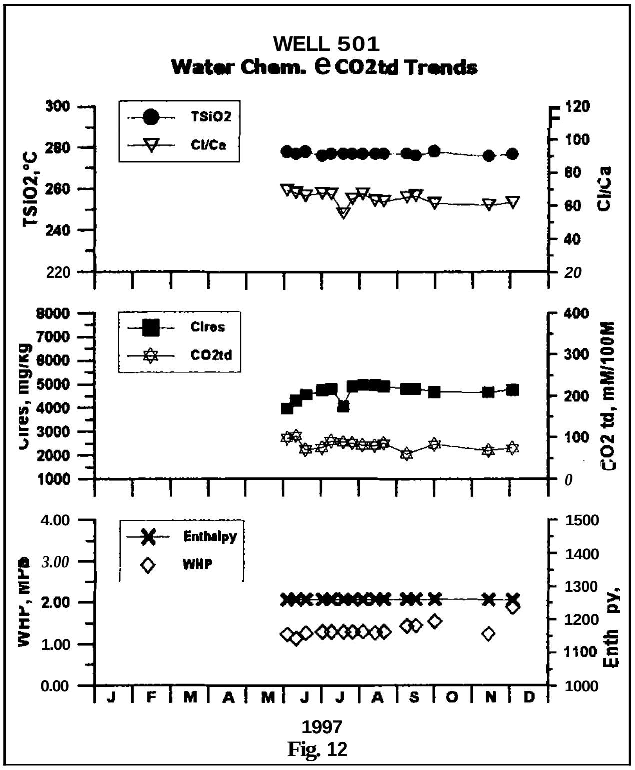

WELL 501
Water Chem. e CO2td Trends
TSiO2
Cl/Ca
TSiO2,°C
Cl/Ca
300
280
260
240
220
120
100
80
60
40
20
Clres
CO2td
Clres, mg/kg
CO2 td, mM/100M
8000
7000
6000
5000
4000
3000
2000
1000
400
300
200
100
0
Enthalpy
WHP
WHP, MPa
Enth py,
4.00
3.00
2.00
1.00
0.00
1500
1400
1300
1200
1100
1000
J
F
M
A
M
J
J
A
S
O
N
D
1997

Fig. 12

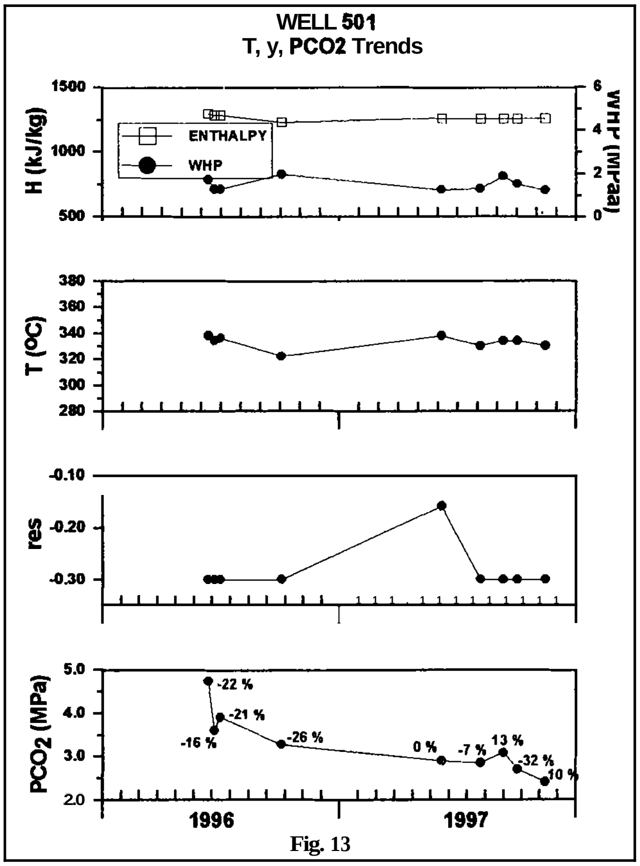

WELL 501
T, y, PCO2 Trends
ENTHALPY
WHP
H (kJ/kg)
WHP (MPa)
1500
1000
500
6
4
2
0
T (ºC)
380
360
340
320
300
280
res
-0.10
-0.20
-0.30
PCO2 (MPa)
5.0
4.0
3.0
2.0
-22 %
-21 %
-16 %
-26 %
0 %
-7 %
13 %
-32 %
10 %
1996
1997

Fig. 13