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APPLICATION OF GAS GEOCHEMISTRY TO EVALUATE RESERVOIR PROCESSES IN THE MINDANAO GEOTHERMAL PRODUCTION FIELD, PHILIPPINES

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ABSTRACT

The geochemical evaluation focuses on the use of gas discharge compositions and equilibria involving H2, H2S, CH4 and CO2 to estimate tempemture and vapor fraction in the reservoir. Physical processes that occurred during the exploitation of Mindanao Geothermal Production Field (MGPF) from 1997 to 2001 are assessed by trend variations through time using Fischer-Tropsch and the pyrite-magnetite reaction grid diagram. Initial state of gas equilibria at the onset of production indicates a vapor loss of 0.1 to 1% at equilibrium tempemture of 245°C in Marbel. Near zero initial steam fraction at 290-305°C suggests near-liquid conditions in Sandawa ***production sector.*** *The variations in trends from 1998 to 2001 in APO3D and SK2D show a decrease in "y" values by as much as 5% and a shift indicating an increase in temperature. Small differences in the FT-HSH values in high tempemture wells like SK3D, KN2D and KN3B suggests near equilibrium conditions with an initial steam fraction of 0.5-5%. The shift in FT-HSH trend signifies degassing of high temperature fluids in Sandawa at 290-300°C resulting to vapor gain in nearly all wells reaching Marbel sector. Vapor gain implies increase in* ***liquid*** *contribution coming from the hotter Sandawa sector.*

1.0 INTRODUCTION

The Mindanao Geothermal Production Field (MGPF) is located in the island of Mindanao and is the fourth geothermal field developed by PNOC-EDC. It has a total of 104 W e installed capacity and was developed in two stages, each consisting of 2x52 W e steam turbines. Commercial exploitation of the field started in 1997.

The application of water geochemistry has been successfully applied in assessing and evaluating reservoir processes in water-dominated geothermal systems. The application of gas chemistry in MGPF complemented the water geochemistry in evaluating subsequent reservoir conditions and response due to exploitation. The method applied here uses gas equilibria as described by Giggenbach (1980) and further developed by D'Amore and Celati (1983) and D'Amore and Truesdell (1985). Subsequent workers in the Philippines provided an application of gas chemistry where Salonga and Auman (1997) evaluated the state of gas equilibria in the Tongonan production wells and thermal areas. Salonga et al. (1999) later expanded the gas equilibria based on Fischer-Tropsch and the pyrite-magnetite reaction that included a third gas equilibrium reaction pyrite-magnetite-ammonia (SNHC) in evaluating well processes.

The model developed by D'Amore and Truesdell (1985) is used in this study to establish the state of gas equilibria in the production wells at the onset of mass extraction in 1997. It was also used as an additional tool to confirm the physical processes that occurred in over five years of production, as established by the conventional water and gas chemistry monitoring tools. Estimated temperatures and mass steam fraction "y" variations of six production wells are plotted in the Fischer-Tropsch (FT) and the pyrite-magnetite reaction (HSH) grid diagram. The wells selected represent a cross section of the field that exhibited changes in reservoir conditions during the given period. Near equilibrium conditions at reservoir temperature of 300°C is indicated based on the total gas discharge of KN2D and KN3B wells. On the other hand, non-equilibrium conditions are represented by gas discharges of Marbel wells such as APO3D and SK2D, reflecting a considerable disparity in the calculated chemical parameters FT and HSH. The disproportion however, is extrapolated to signify separate reservoir conditions.

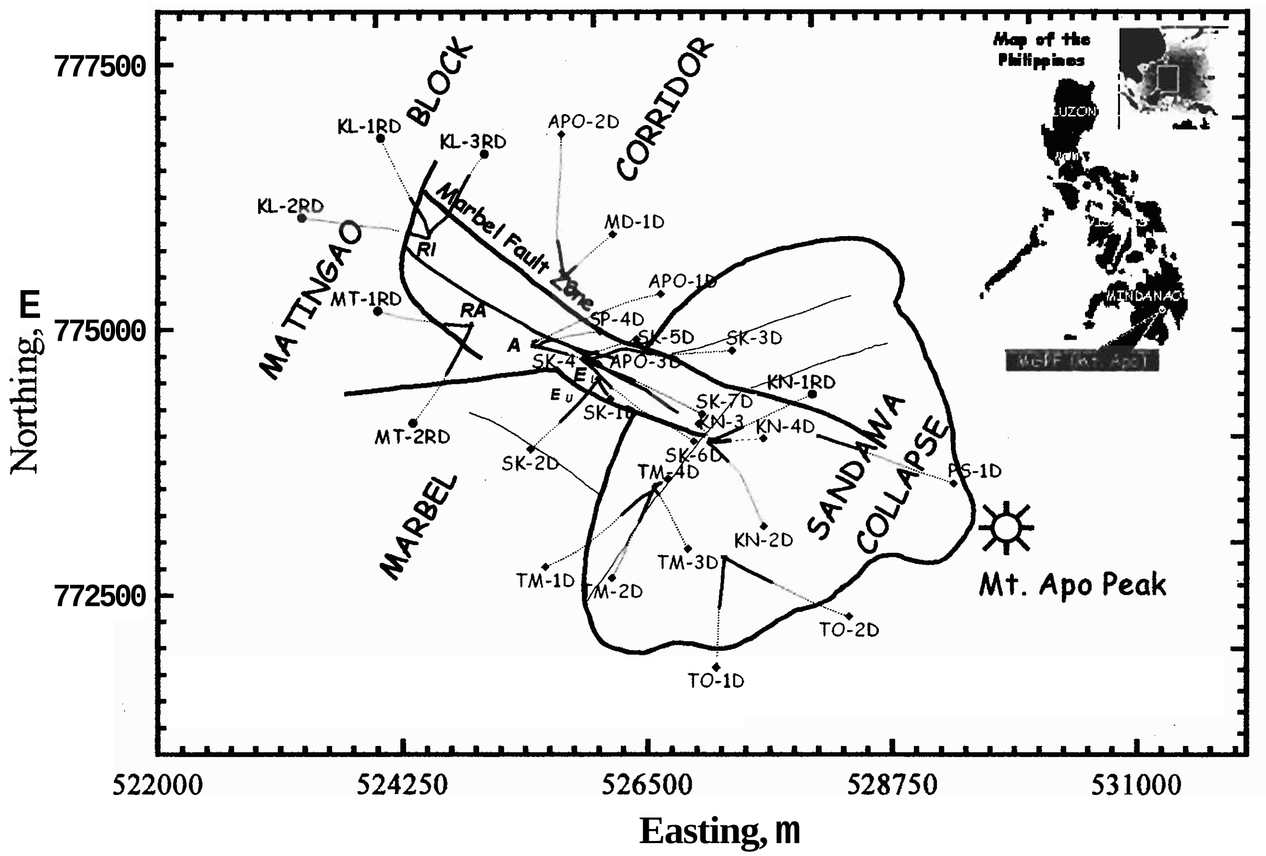

Figure 1. Map of the Mindanao geothermal production field showing the three geographical sectors Matingao, Marbel and Sandawa.

2.0 PRODUCTION AND INJECTION HISTORY

The Mindanao geothermal production field is divided into three geographic sectors from northwest to southeast namely, Matingao-Kullay, Marbel, and Sandawa (Figure 1). Power generation was developed in two stages. The first 52 MWe power plant (M1GP) was commissioned in March 1997 although start-up and prolonged well discharge tests were underway since 1994. There are presently ten production wells from the Marbel sector supplying steam to MIGP. By February 1999, the second 52-MWe power plant (M2GP) underwent pre-commissioning activities and was in commercial production by June 1999. The power plant is principally supplied with steam by seven production wells from Sandawa. About 3 MWe is supplemented by a secondary flash system produced from 900 TPH mixed fluids from MIGP and two wells (MD1D and APO2D) at pad B. Brine injection utilizes six injection wells located in the Matingao-Kullay sector. The brine coming from the Sandawa separator stations is disposed in a single in-field injection well KN1RD.

Table 1 summarizes the total mass extracted and injected since commercial production began in MIGP and M2GP.

Table 1. Mass extraction and injection in MIGP and M2GP (Trazona. 2001).

	MIGP (tons)	M2GP (tons)	Total (tons)
Mass	5.9e07	1.5e07	7.5e07
Mass injected	4.3e07	5.4e06	4.9e07
%Gross	8.7	2.3	11.0
%Net	2.3	1.5	3.8

3.0 RESERVOIR CONDITIONS

The hottest part of the field occurs beneath Sandawa where temperatures in excess of 300°C are encountered at about -250 mRL. High chloride waters come from this region and undergo boiling and dilution. A lateral flow towards the northwest beneath Marbel produces diluted fluids that correspond to lower temperatures of 240-260°C. Lower measured temperatures of <220°C are encountered further west towards Matingao-Kullay. which represents the oufflow region. The major structural features such as the Marbel Fault Zone generally controls the hydrology of the geothermal field.

By 1998, indications of injected fluid returning to some production wells in Marbel namely, APOID, APO3D and SK2D, were evident due to increased mineralization with corresponding decline in gas concentrations in the discharge. The chemical change intensified until the third quarter of 1999 affecting other wells. However, the reduction of injection load employed at the Matingao injection wells alleviated the persistent progress of injection returns.

Also in 1999, the onset of mass extraction in Sandawa sector due to commercial operation of the second power plant induced temporal chemical changes. By the year 2000, increasing gas discharge trends particularly H2S concentrations signified recharge from Sandawa. The present geochemical trends indicate stable reservoir conditions suggesting a balance between mass extraction and mass injection.

4.0 RESERVOIR TEMPERATURE TRENDS

The deepest well drilled in Sandawa, KN3B, showed a downhole temperature of 300°C at -250 mRSL following a prolonged well discharge test in 1996. Quartz-based geothermometer established a temperature in excess of 320°C indicating a supersaturated fluid. Cation-based geothermometers, T(Na-K-Ca) and T(Na/K), provided a temperature range of 300-315°C. Nearby wells likewise indicated high temperatures in excess of 280°C. The comparable temperatures from these geothermometers and downhole measurements evidently established the hottest region found in Sandawa where high-Cl geothermal fluids emerge. The migration of these fluids northwest towards Marbel at –200 mRSL produced more dilute, lower temperature fluids ranging from 240-260°C.

Table 2 summarizes the gas discharge parameters used in this study. Apart from injection returns affecting Marbel wells, measured reservoir temperature trends across the field have remained virtually at the Same levels since the onset of production. In Marbel though, there is an indication of temperature decline based on the Na-K-Ca geothermometer. But the likely disparity is a result of Ca supersaturation at this part of the reservoir causing non-equilibrium conditions. The chemistry of the fluids appears to be re-equilibrating at lower temperatures as a consequence of injection fluids from Matingao. However, recent downhole measurements in the Marbel well, SP4D, indicated a temperature of ~245°C at the feed zone.

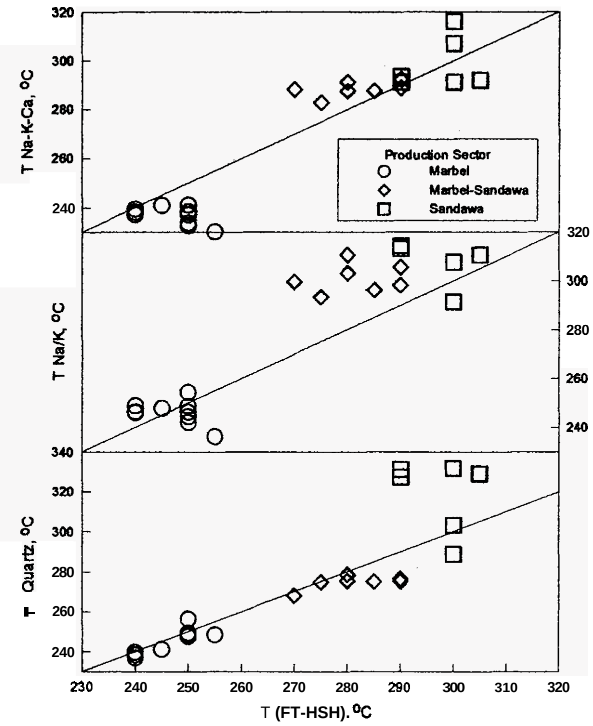

Figure 2. Temperature T_{FT-HSH} compared to water geothermometers. Diagonal line indicates temperature equivalence.

The estimated FT-HSH equilibrium temperatures of selected production well discharges with the water geothermometers are shown in Figure 2. The temperature is derived using an iterative method equating FT and HSH values. The values in Table 2 are averaged for each year period or selected number of months in the case for 1999. The diagonal line corresponds to equivalence in the estimated temperatures between FT-HSH and the selected geothermometers.

Table 2. Total discharge gas composition from selected wells and computed parameters.

DATE H (J/g)	CO2 td	H2S td	NH3 td	H2 td	N2 td	CH4 td	FT	HSH	tQtz	tNaK	tNKC	tCH4	t NH3	tDAP	y	T_{FTHSH}
	41.050	0.743	0.072	0.019	0.702	0.008	-23.164	-8.673	241	248	241	218	229	187	-0.01	245
	17.358	0.762	0.019	0.018	0.534	0.008	-23.583	-8.620	240	246	237	212	250	210	-0.008-0.01	240
	17.825	0.740	0.062	0.017	0.433	0.008	-23.684	-8.631	238	246	238	211	227	208	-0.008-0.01	240
	19.529	0.818	0.045	0.022	2.775	0.009	-23.304	-8.603	237	249	239	216	253	211	-0.005	240
	20.246	0.879	0.071	0.015	1.444	0.008	-23.880	-8.348	249	236	230	208	231	202	-0.03	255
	32.746	2.060	0.094	0.070	0.707	0.015	-21.263	-7.906	249	242	233	244	257	233		250
	36.543	1.387	0.077	0.067	0.700	0.013	-21.253	-8.398	249	254	241	244	260	224		250
	23.857	1.123	0.061	0.062	0.433	0.009	-21.411	-8.641	249	249	238	242	258	236	-0.003	250
	25.102	2.265	0.074	0.092	0.351	0.007	-20.613	-7.898	248	246	237	254	263	257		250
	25.178	1.828	0.069	0.097	0.351	0.007	-20.478	-8.202	256	244	234	256	266	256		250
SK3D																
10/27/97 1549	158.633	5.641	0.097	0.437	0.920	0.134	-18.366	-7.386	276	306	292	289	302	226	-0.004	290
03/24/98 1422	88.271	3.078	0.118	0.170	0.303	0.027	-19.574	-7.765	278	311	291	270	265	225	-0.01	280
08/26/98 1384	121.066	4.052	0.137	0.361	0.855	0.040	-18.289	-7.735	275	303	288	290	292	236	0	280
03/25/99 1285	80.926	2.476	0.129	0.257	0.923	0.046	-19.114	-8.229	268	300	288	277	285	232	-0.001	270
07107199 1295	87.543	2.940	0.113	0.321	0.727	0.039	-18.628	-8.101	275	293	283	285	291	239	0	275
05/23/00	85.708	5.333	0.123	0.229	1.382	0.037	-19.201	-7.179	275	296	288	275	286	239	-0.015	285
06/21/01 1422	91.289	4.675	0.158	0.232	0.933	0.043	-19.214	-7.356	275	298	289	275	278	234	-0.015	290
SK1D																
10114197 2600	268.273	11.040	0.240	0.706	0.372	0.051	-16.885	-6.720		238		314	288	241	0.025-0.6	240-275
05122198 2780	428.268	30.105	0.370	3.301	2.880	0.089	-14.243	-6.083	253	229		362	340	280	0.08-1.0	240-270
08/26/98 2692	377.932	16,363	0.308	1.573	1.219	0.046	-15.298	-6.555	237	243	226	342	315	259	0.05-0.6	240-275
07/19/99 2639	334.318	12.766	0.207	2.687	1.768	0.076	-14.641	-7.111	232	245	233	354	340	270	0.08-0.4	240-275
06/07/00 2639	370.602	15.926	0.282	2.887	2.598	0.080	-14.493	-6.854	235	245	235	357	340	272	0.08-0.7	240-275
11121/00 2699	387.153	18.351	0.348	2.722	1.872	0.064	-14.481	-6.644	240	247	238	357	332	273	0.08-0.4	240-275
07/20/01 2698	359.769	16.216	0.328	2.554	1.286	0.051	-14.522	-6.777	256	237	229	357	328	274	0.08-0.4	275-280
KN2D																
06/29/99 1547	76.842	6.016	0.009	0.772	1.672	0.051	-17.269	-7.550				307	365	278	0	290
08/18/00 1644	81.271	12.024	0.087	0.829	0.794	0.031	-16.913	-6.678	289	291	307	313	319	294	0	300
07/10/01 1644	82.224	8.873	0.132	0.492	0.488	0.017	-17.554	-6.848	303	291	316	302	293	278	0	300
KN3B																
06/23/99 1747	102.239	5.899	0.061	0.633	0.980	0.053	-17.508	-7.489	331	314	291	303	320	260	0.001	290
05/15/00 1676	89.432	8.086	0.021	0.615	0.704	0.035	-17.433	-7.066	327	313	293	304	335	273	-0.001	290
07/18/00 1676	88.716	9.778	0.026	0.609	0.591	0.034	-17.447	-6.814	329	311	292	304	330	277	-0.008	305
07/10/01 1645	96.495	7.293	0.015	0.626	0.516	0.031	-17.325	-7.208	332	308	291	306	339	271	-0.001	300

A good correlation is established between the quartz geothermometer with respect to FT-HSH across the field except for silica supersaturated fluids found in KN3B. The cation geothermometers on the other hand, indicate contrasting differences. For instance, APO3D in Marbel, which is affected by injection returns, exhibits departure from equivalence following T(Na-K-Ca) but not T(Na/K). On the other hand, high temperature wells from Sandawa show improved correlation in terms of T(Na-K-Ca) but T(Na/K) reflects a slightly higher difference. The variations are likely a consequence of equilibration rates of the geothermometers respective of the prevailing reservoir condition. Comparable temperatures are reflected for fast re-equilibrating geothermometer as in the case of quartz while the Na/K geothermometer gives a higher difference since deep temperatures are reflected where the fluid may have last equilibrated. T(Na-K-Ca) on the other hand which considers Ca-correction, gives a lower difference resulting from slower re-equilibration to lower temperature. The FT-HSH temperature, which is derived from gas constituents involving principally CH4, H2, H2S and CO2, reflects fast re-equilibration condition assuming full equilibrium.

Figure 3 shows the estimated FT-HSH temperature comparison with selected gas geothermometers. Nearly all the gas geothermometers reflected a difference in injection affected or gas-depleted fluids, e.g. APO3D. For high temperature wells in Sandawa acceptable correlation is demonstrated by ammonia and methane geothermometers. The lack of congruence for T(DAP), which shows lower temperature estimates, could be attributed to the adjustment of C02 contents to the prevailing temperature condition (Giggenbach, **1980).** An FT-HSH temperature estimate reflects full equilibrium condition at the given gas reaction concentrations.

5.0 STEAM FRACTION TRENDS IN MGPF

The FT and HSH parameters are calculated from the gas discharge concentrations of the selected wells. The corresponding steam fraction **"y"** results, which are simultaneously derived with temperature from data nearest to the average for each period, are shown in Table 2.

Wells APO3D and SK2D are located at the Marbel sector. Both of these wells are affected by reinjection returns but displayed varying response using the FT and HSH method.

Steam fraction "y" in APO3D indicates vapor loss varying from **-1%** in **1998** to -0.5 to -0.8% in **1999** and 2000, to -3% in **2001.** Vapor loss **is** contiguous until the present period however, at an estimated temperature of 255°C. The temperature increase in this case does not coincide with the actual temperature at –245°C measured during the period. Figure 4 shows the FT-HSH trend in APO3D plotted in the grid

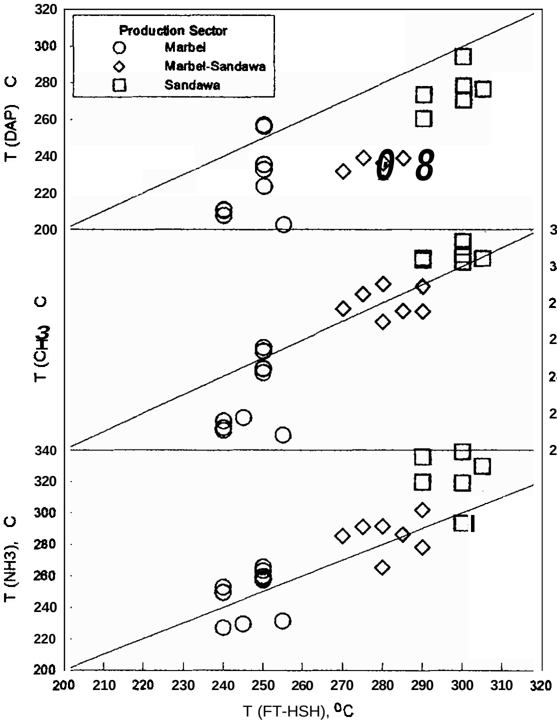

Figure 3. Temperature, $T_{FT\text{-}HSH}$, is compared with gas geothermometers. Diagonal line indicates temperature equivalence.

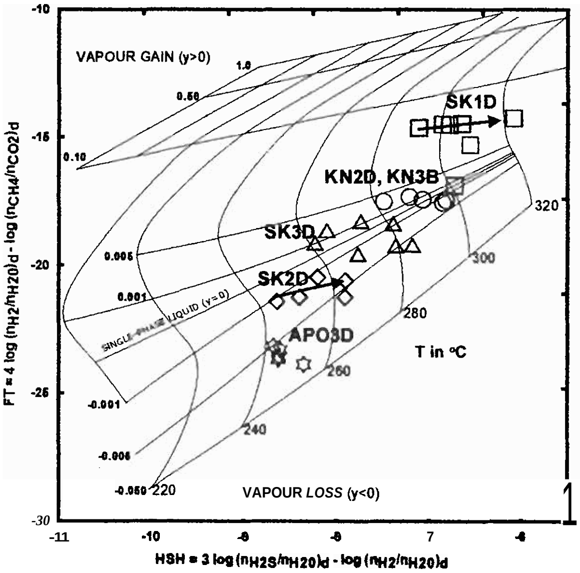

Figure 4. FT-HSH plot diagram showing trends across Mindanao geothermal production field from 1998 to 2001. Trend plot characterized with increasing temperature and a decline in steam fraction "y" (vapor loss).

diagram. The expected "y-shift" should be towards the lower left corner of the grid as a response to reinjection fluids and would have resulted to equilibriate at a lower temperature (<240°C). Instead, a positive shift is depicted analogous to an increase in temperature. The unexpected response of the gases suggests another separate process influencing the discharge characteristics of this well and not solely by the reinjection returns.

There is disagreement between FT and HSH values calculated with equilibrium values equivalent to the temperature and steam fraction "y" in **SK2D**. The difference signifies several possible equilibrium conditions in each of FT **(H2-CH4/CO2)** and HSH **(H2-H2S)** reactions correlating to different temperatures and steam fractions. For instance in 1998, the average FT value is -21.253 and HSH is -8.398 corresponds to an equilibrium temperature of –270°C and steam fraction -0.015 to -0.02. Actual temperature of SK2D during the period vaned from 240-250°C where FT and HSH should have expected values ranging from -21.7 to -20.8 and -9.3 to -8.7, respectively. At this temperature range, FT-HSH reaction should indicate a steam fraction of -0.005 to 0. But the difference however presented indicates a vapor loss of 0.12-0.70% based on FT reaction while HSH shows a vapor gain of 12-24% at a temperature range of 240 to 260°C. This behavior suggests a non-equilibrium condition prevailing in the reservoir. SK2D discharge characterizes a non-equilibrium condition as a consequence of interplay of feed zones. The well produced from a shallow dominantly two-phase in the early production stage and presently, from the deeper feed zone characterized by the more hotter and liquid discharge. The foregoing change in dominant feed zone suggests high temperature vapor in the discharge, and can also explain the vapor recharge emanating from degassing high temperature fluids. The positive shift invoked by the HSH parameter with respect to temperature and the decline in steam fraction **"y"** relates to the initial steam fraction or vapor loss of the parent fluid, which is the high temperature fluid.

The trends of high temperature wells SK3D, KN2D and KN3B as shown in Figure 4, depict similar trends with temperatures ranging from –265 to 285°C and 290 to **305°C**, respectively. However, there is a lesser difference in FT and HSH values in the latter wells, which suggests near equilibrium conditions in the reservoir. Furthermore, this suggests degassing or boiling occurring near the well bare.

SKID is a shallow well, which tapped the highly two-phase reservoir, and discharges mainly dry steam. Far beyond the expected temperature estimates is shown by this well at **>290°C** corresponding to a large positive shift. Again the presence of high temperature vapor in SKID as established by FT-HSH evidently signifies vapor recharge from a hot source. This observation is also observed in nearly all wells, including injection affected wells in Marbel, indicating vapor recharge from Sandawa. From the stable geochemical trends presently observed in the reservoir, deep liquid recharge may follow as evident from the geochemical characteristics found in SK2D.

6.0 SUMMARY AND CONCLUSIONS

The FT-HSH gas equilibria method provided an alternative evaluation method of reservoir processes on response to exploitation. Using this method, in addition to the established tools gave additional refinements in the interpretation of reservoir response and in defining strategies to be adopted in future developments.

There are **two** principal parameters calculated from the gas total discharge concentrations namely, the fluid temperature and initial steam fraction, T_{FT-HSH}, is comparable to T_{Quartz}, However, non-equivalent values are encountered and are due to silica-supersaturated fluids such as KN3B. This situation provided the limitation of application of this method. The lack of congruence with other gas geothemometers could be attributed to the adjustment of the individual gas parameters involved in the reaction as an effect of equilibrium condition. Since the start of mass extraction, there is no significant change in the reservoir temperature across MGPF based on the T_{FT-HSH} results. The temperature estimated for the parent fluids remains at 290-305°C.

The initial steam fraction based on the FT-HSH reaction shows a distinctive trend indicating an increase in temperature and a decline in steam fraction "y" (vapor loss). The incomparable results between the FT and HSH reaction values simply indicate non-equilibrium reservoir conditions. Hence, the unlikely trend signifies possible separate reservoir processes dependent primarily on prevailing equitibrium conditions. The positive "shift" invoked by the HSH parameter relates to the initial steam fraction or vapor loss of the parent fluid. The parent fluid emanating from Sandawa shows a vapor toss of 0.5-5% at a temperature of 290-300°C. Secondary degassing event is implied from intermediate well discharges such that vapor recharging SK2D emanates from fluids with a temperature of 270°C. The temperature indicated by SKID is in excess of 300°C. The presence of high temperature vapor in the Marbel well discharges is an evidence of recharge from Sandawa.

Correlating the positive "shift" to the overall reservoir response shows that vapor recharge began in late 1999 and continued well into 2000. Gas total discharge concentrations during this period indicated an increase. Stable geochemical trends ensued in 2001 suggesting a balance between mass extraction and mass injection have been attained. It is likely then that initial drawdown have occurred upon mass extraction in Sandawa by 1999 inducing vapor recharge to Marbel and intermediate Marbei-Sandawa wells. Subsequently, the expected continuous reservoir drawdown appears to have slowed down suggesting that mass recharge of the hotter liquid is taking place. The geochemical stability attained also suggests that the reservoir was able to cope up with the expected drawdown.

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