A HYDROGEOCHEMICAL MODEL OF THE TONGONAN GEOTHERMAL FIELD

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ABSTRACT

Chemistry and enthalpy data have been used to identify the Upper Mahiao reservoir fluids as the most mineralized high temperature region of the Tongonan field so far drilled. Broad cooling and dilution trends have been delineated together with directions of preferential steam migration. The response of discharge enthalpy and fluid chemistry to changing wellhead pressure is described and its importance in chemical interpretation is stressed. The permeability of structural features is discussed and the possibility of some structural control on hydrology is considered.

PROJECT HISTORY

The Tongonan Geothermal Field is located on the island of Leyte in the Republic of the Philippines and is associated with the Philippine Fault Zone which strikes northwest through the island arc system.

Exploration drilling began in 1974 with shallow temperature gradient wells sited on the basis of surface geology and distribution of major surface manifestations, particularly hot chloride water discharging from the Bao Springs. Deep drilling commenced in 1977 with well 401, the first well to tap the deep high temperature (over 300°C) chloride water that is typical of the Tongonan geothermal reservoir. Figure 1 shows the distribution of wells in the Tongonan field as of early 1982. The Lower Mahiao and Sambaloran sectors will supply steam to the 112.5 MW Leyte I Power Station in late 1982 and currently the Malitbog sector is being developed for a second station.

GEOLOGY OF THE TONGONAN FIELD

At Tongonan andesitic volcanics plus minor marine sediments are found to 2 km below sea level. The andesite is intruded in the central part of the field by a diorite body. The topography of the upper surface of this diorite pluton, which has been closely defined by drilling is shown in Figure 1 (Palma 1981). The contact between the andesite and diorite pluton comprises andesites, microdiorite/diorite dykes and andesite/diorite breccias. This has been called the Transition Zone and it has permeability which is considered to be associated with the emplacement of the pluton.

The Philippine Fault Zone with conjugate minor faults has contributed significantly to the present-day structure of the field.

GENERAL GEOCHEMISTRY

Table 1 lists chemical data for Tongonan well waters separated at atmospheric pressure and for steam separated at higher pressures. The data are those collected under throttled, high wellhead pressure conditions when the total discharge enthalpy is generally lowest. The discharge waters are typically neutral pH sodium chloride brines with accompanying potassium and Significant calcium and boron. Non-condensable gas concentrations vary considerably throughout the field with CO_2 ranging between 40 and 800 mmoles/100 moles in the total discharge.

The Bao Valley neutral chloride springs are the most impressive surface manifestations in the Tongonan field and wells TGE 4 and 5 intersected the same fluid at shallow depth. The chemical

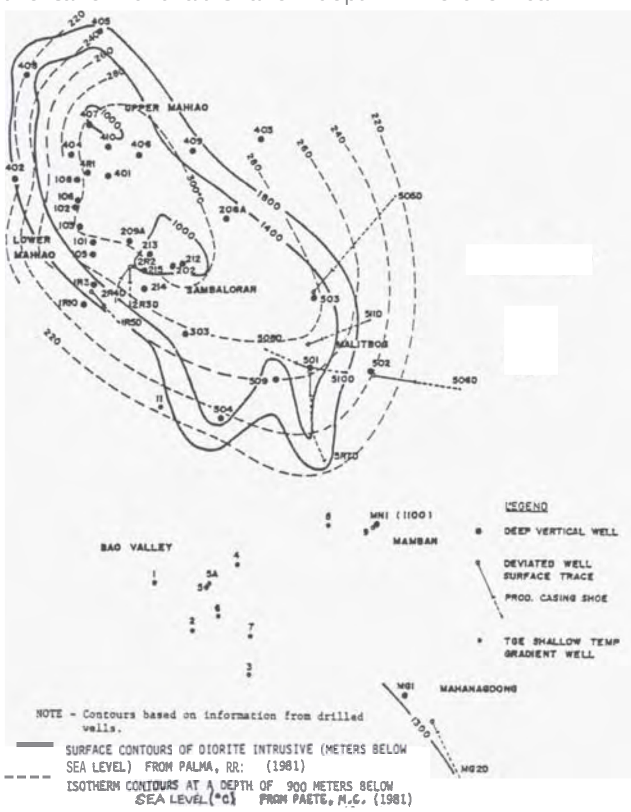


Figure 1: Tongonan Geothermal Field

Table 1:

WATER AND STEAM CHEMISTRY OF TONGONAN WELLS UNDER THROTTLED CONDITIONS (HIGH WELLHEAD PRESSURE) FOR SELECTED SAMPLING DATES DURING MEDIUM TERM DISCHARGE TEST

WELL NO	DATE dd mm yy	WHP MPa	H° J/g	TMF kg/s	pH	Cl mg/kg	Na	K	Ca	8	SO4	SiO_2	Cl_{AQ} (1)	Cl/B MOLEC	$TSiO_2$ (2)	CO_2 (3)	H_2S (3)	CO_2/H_2S
							in water	at	atmospheric			pressure						
103+	11 08 78	2.74	1120	31	6.9	13100	6813	1947	234	-	-	981	8500	-	278	56	1.2	45
105	01 02 79	3.26	1220	45	7.1	12400	6375	1707	-	229	-	914	8000	16.5	273	61	2.7	22
108	12 06 80	3.25	1460	12	7.1	12090	6460	1680	231	267	-	972	8100	13.8	278	407	7.9	51
2R2	11 09 79	2.69	1650	25	7.2	12860	6948	1681	216	247	39	1096	7600	15.9	289	188	5.4	35
208A	14 03 80	4.03	1490	10	-	12370	6601	1719	171	220	21	1082	7200	17.1	291	133	8.5	16
209A	20 02 81	5.46	1550	9	6.2	13800	7120	2040	177	249	-	1191	8400	16.9	302	36	3.9	9
213	17 09 79	4.17	1310	45	6.8	13650	7147	1892	230	265	39	1135	8200	15.7	292	63	3.5	18
214	21 07 79	3.38	1310	38	7.4	11620	6246	1580	228	211	29	917	7900	16.8	273	122	2.0	62
303	15 07 80	1.82	1170	88	7.1	10600	5505	1410	273	187	31	859	7000	17.3	268	31	1.3	24
401	09 03 82	3.46	1700	49	6.6	16320	8888	2420	302	358	32	1021	10300	13.9	279	188	11.5	16
402*	22 12 80	0.43	1620	6	4.0	6500	4041	617	58	152	2270	522		13.0	227	3856	73.0	53
403	08 01 81	2.51	1280	9	7.4	10800	5829	1393	183	207	22	975	6900	15.9	279	310	4.5	69
404	09 07 81	2.89	1430	39	-	12700	6802	1575	300	298	-	756	8200	13.0	258	437	4.8	91
405	17 12 80	2.49	1150	25	7.3	11880	6294	1462	275	252	33	797	8000	14.4	262	166	1.8	93
406	09 07 79	4.30	1600	23	6.9	14340	7245	1940	293	306	29	1229	8500	14.3	299	169	6.8	25
407	05 08 78	3.34	1510	25	6.8	16720	8539	2434	248	382	40	1169	9800	13.3	300	430	6.6	65
410	22 09 81	5.54	1740	20	6.6	17330	9130	2380	237	401	34	1350	9500	13.2	~320	281	11.6	24
501	16 01 79	3.2	1210	47	7.5	9066	4920	1249	133	-	17	915	6000	-	271	71	2.6	27
502+	14 08 81	2.49	1040	11	7.9	4785	2594	674	61	69	36	885	3700	21.1	270	107	3.8	28
503	01 04 80	3.17	1250	19	7.4	11370	6079	1480	231	208	24	844	7300	16.7	266	93	1.9	50
504	10 09 80	1.90	1150	14	7.1	8116	4260	962	196	141	52	653	5800	17.6	246	47	2.1	23
5R7*	12 02 82	0.38	1110	19	7.7	4740	2635	454	130	60	78	635	3200	24.1	244	48	1.7	29
508D+	17 02 82	2.84	1030	19	7.4	9561	4578	1251	197	167	30	785	6700	17.5	261	57	1.1	52
509	21 12 81	1.68	1090	33	7.7	7345	3759	867	171	112	34	679	5000	20.0	249	73	1.2	60
5100	24 02 82	2.64	1120	12	7.6	7773	3798	972	161	127	31	812	5500	18.7	263	72	1.5	48
5110	10 04 82	3.72	1230	11	7.1	9673	4911	1314	176	167	21	939	6200	17.7	275	487	7.7	63
MG1	09 05 81	3.07	1210	12	8.1	4065	2345	381	21	59	37	851	2700	21.0	267	218	1.6	134
MG2D+	09 12 81	2.59	982	38	8.1	4072	2311	439	28	60	45	791	2800	20.7	261	67	0.8	80
TGE 4*	01 11 75	0.65	815	-	8.2	3794	2194	239	86	35	90	378	3100	33.1	209	~17	-0.2	~60
HS#4	26 04 82	-	(boiling)	-	-	3868	2120	215	108	38	84	304	-	31.0	210	-	-	-
HS#12	26 04 82	-	(67°C)	-	8.1	3602	1982	186	85	33	78	258	-	33.3	198	-		

NOTES:
WHP - WELLHEAD PRESSURE
H° - TOTAL DISCHARGE ENTHALPY
TMF - TOTAL MASS FLOW
HS - Bao Valley Hot Chloride Spring
* - Well not throttled during discharge test.

(1) Calculated Deep Aquifer Chloride Concentration (mg/kg); See Text.
(2) Silica Geothermometer Temperature ("C); From FOURNIER, R.O. and ROWE, J.J. (1966). Corrected for excess discharge enthalpy.
(3) Concentrations expressed as mmoles/100moles in total discharge.
t Wells with anomalously low discharge enthalpies; see text.

homogeneity of the Bao Valley chloride springs and their close proximity suggests they have a common parent source.

Boron and arsenic in the well fluids are the toxic constituents of greatest concern and have made reinjection of separated wastewater a necessary part of the project development.

DOWNHOLE TEMPERATURE PROFILES

From an analysis of the temperature profiles measured in most wells in the Tongonan field isotherm contours have been developed for various depths of the field (Paete 1981). These contours have been found to resemble the surface contours of the diorite pluton as shown in Figure 1. However temperature inversions in some wells and particularly in the Malitbog sector have shown that the recorded temperatures do not directly correspond to inherent diorite rock temperatures but are more a result of reservoir fluid flowing from a higher temperature region.

GEOCHEMISTRY AND MEDIUM TERM DISCHARGE TESTS

Most of the geochemical data presented in this paper have been collected during a 6-12 week discharge of the wells, designed to give stable output and chemical data under both full bore discharge (FBD) and throttled conditions when the wellhead pressure (WHP) approaches the Maximum Discharge Pressure. After stable output is attained under FBD (low WHP) the well is throttled in one week stages using successively smaller orifice plates. The chemical response to increasing WHP is found to be central to the understanding of well discharge processes.

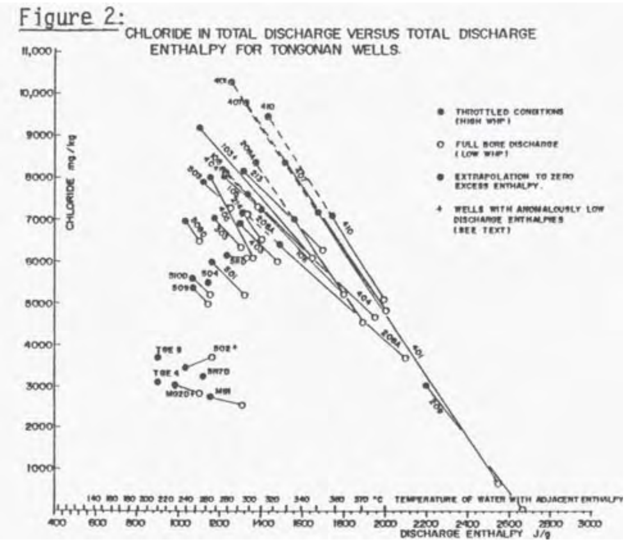
EXCESS ENTHALPY IN TONGONAN WELLS

Under FBD most wells in the Mahiao and Sambaloran sectors develop excess enthalpy, that is, total discharge enthalpies greater than the enthalpy of single-phase fluid at the reservoir temperature calculated from silica concentration. Many Tongonan wells have upper two-phase zones above the deep single-phase reservoir. Excess enthalpy is considered to be primarily derived from boiling in this upper zone, however in some of the hotter wells downhole surveys under flowing conditions have indicated two-phase conditions in the deep reservoir.

Tongonan wells exhibit highest discharge enthalpy under FBD and with throttling to higher WHP enthalpy usually declines to that of a single-phase fluid at the reservoir temperature. This is in contrast to some fields where vapor zones cause an increase in enthalpy at high WHP (Grant 1979). Some hotter Tongonan wells retain excess enthalpy even at high WHP while wells drilled in the cooler Malitbog reservoir generally do not develop significant excess enthalpies even under FBD.

ESTIMATING DEEP AQUIFER CHLORIDE CONCENTRATION

It is found for all high-enthalpy Tongonan wells that there is a consistent inverse linear



relationship between total discharge chloride concentration (Cl_{TD}) and total discharge enthalpy (H_{TD}). Figure 2 shows the linear regression lines of Cl_{TD} vs H_{TD} plots for all wells tested in Tongonan. This relationship can be explained in terms of dilution under FBD conditions by high enthalpy steam from a separate low-chloride two-phase feed, or alternatively by preferential entry of steam as boiling develops in the reservoir. In this paper the deep aquifer chloride concentration is obtained directly from the Cl_{TD} vs H_{TD} plot at the point where H_{TD} equals the reservoir temperature obtained from the silica geothermometer. This is the point where Cl_{TD} reaches a maximum and steam dilution is lowest. For the few wells that retain excess enthalpy even at higher WHP the Cl_{TD} vs H_{TD} plot is extrapolated to the single-phase condition. In Table 1 are presented the deep aquifer chloride concentrations calculated by the above method for all Tongonan wells that have undergone medium term discharge tests. The anomalously low measured enthalpies of some wells, based on silica and measured downhole temperatures, (Table 1), are considered unreliable and are not used in aquifer chloride calculations.

HYDROGEOCHEMICAL TRENDS ACROSS THE TONGONAN FIELD

In Figure 3 deep aquifer iso-chloride contours are mapped across the field. Aquifer chloride is found to be highest in the Upper Mahiao sector and declines in all directions away from this region. The most marked decline that has been observed is across the Malitbog sector, where on the southern periphery chloride approaches that of the TGE wells (approx. 3500 mg/kg).

Silica geothermometer temperatures (Fournier and Rowe 1966) are presented as contours in Figure 4. Well 410, the deepest well tested in the Upper Mahiao sector shows the highest silica temperature of 315-320°C. Temperatures are seen to decline to the west (Well 402), to the north (405), and to the east, (403) but remain high towards the Sambaloran sector. A more rapid decline is observed due south towards Well 504 (245°C) but temperatures remain considerably higher in the eastern Malitbog, (Well 511D, 276%).

Figure 3: Deep Aquifer Chloride Concentration (mg/kg) Contours

An aquifer chloride verses silica temperature plot used for inferring dilution and heat transfer processes in the reservoir is shown in Figure 5. Although this graphical method has the limitation that a combination of processes can be used to invoke hydrological connections between most wells it is nevertheless useful for indicating more probable hydrological connections.

Three cooling-by-dilution trend lines are shown in Figure 5. Line A suggests a possible dilution pathway from Well 410 through 208A to 502. Line B suggests the shallow TGE wells 4 and 5 lie at the end of a dilution pathway through Wells 213, 508D and the southwestern Malitbog Wells 504 and 509. It appears less likely that the Bao Valley fluid is derived from eastern Malitbog Wells 502 and 5R7D since considerable conductive cooling or loss of steam would be required. Moreover Figures 3 and 4 suggest there are two separate outflows from the Sambaloran sector; to the east (Well 503) and to the south (Well 504).

It also appears that fluid does not flow directly from Well 501 to nearby 502 since the latter is considerably more dilute but at a similar temperature. Chloride and temperature trends support the view that the Malitbog sector is a major outflow zone and suggest further that it is comprised of several separated preferential fluid pathways.

Well 401 appears to have undergone considerable adiabatic boiling and cooling while wells along Line C in Figure 5 have probably been affected by a combination of boiling and dilution, (dilution alone, by 30°C water is not possible at reservoir depths).

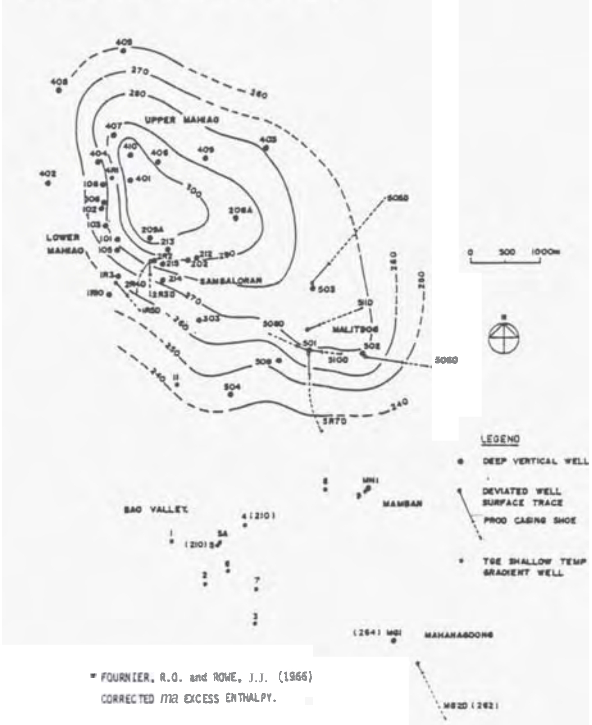


Figure 4: **Silica** geothermometer temperature (°C) Contours

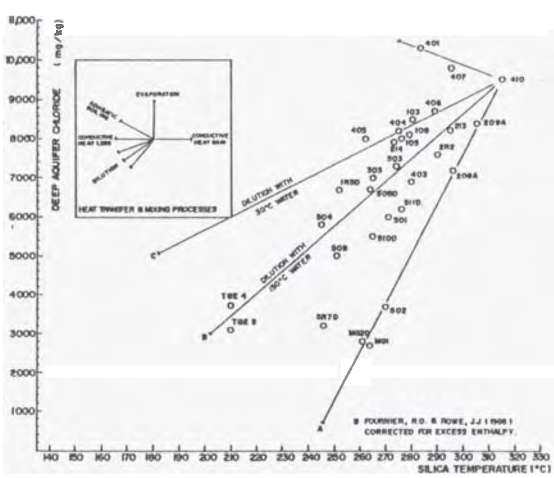
The reservoir fluid of the **two** Mahanagdong wells, **MG1** and **MG2D** is considerably more dilute than that of other deep Tongonan wells and has a temperature of about **260°C,** based on silica concentration. Based on this information and in view of the distance from the rest of the field, the Mahanagdong reservoir is considered to have a separate heat source from that of the northern sectors.

It can be seen from Figure 5 that for reservoir fluid to flow from the Mahanagdong sector to the Bao Valley considerable conductive cooling or loss of steam must occur. The overall geochemical trends suggest the Bao Valley chloride fluid is more likely derived from the north and the chemical homogeneity of the Bao Valley chloride springs makes the possibility of two widely-separated parent sources less likely.

GAS CHEMISTRY

Gas concentrations are known to be highest in the upper two-phase zones of Mahiao and Sambaloran wells, based on the following observations: Under discharging conditions and in the vicinity of the well bore these upper zones become underpressured with respect to the hot hydrostatic pressure curve and relative to the deep zone. At higher discharge pressures the relative contribution from the upper zone is less and for many wells **(e.g.:** 406, 403, 213, **208A)** a marked decline in gas concentration is observed (together with a corresponding increase in total discharge chloride). Shallow wells 208, 209 had considerably higher gas levels before they were redrilled and deepened **(208A, 209A).** Well 403 showed highest gas levels early in the discharge when production was predominantly from shallower levels.

Figure 5: CALCULATED DEEP AQUIFER CHLORIDE VERSUS SILICA* TEMPERATURE



Gas **data are** included in Table **1** for high wellhead pressure conditions (when gas is generally lowest). Highest gas concentrations are found in Upper Mahiao wells and peripheral wells to the west **(402, 408)** and east **(403, 208A).** The very high-gas acid-sulphate fluid discharged by Well **402** appears related to the acid-sulphate Kapakuhan springs nearby, and suggests the incursion of acid-sulphate fluid derived from the near-surface oxidation of an H_2S-**rich** steam flow. Gas concentrations decline to the south across the Sambaloran and Malitbog sectors. Well **511D** has anomalously high gas concentrations that may be transmitted upwards through narrow channels in the East Philippine Fault which is considered relatively permeable in this region. Well 511D is the first tested well to have intersected this fault.

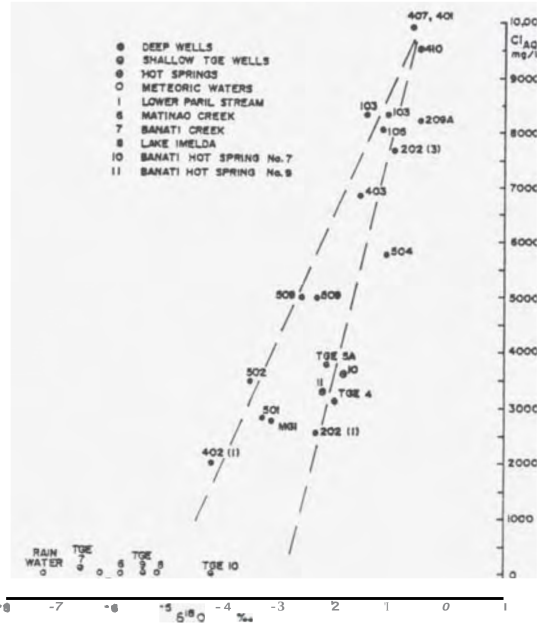
The overall gas trends when considered in conjunction with the chloride and **silica** geothermometer data suggest that gas has migrated with separated steam away from the upwelling zone along preferential routes particularly to the west, Well **402, 408,** and also to the east, Wells **208A, 403.**

THE CHLORIDE/BORON TREND IN TONGONAN

The molecular **Cl/B** ratio increases consistently from a value of **14** in the Upper Mahiao to 25 in the southern Malitbog. **Cl/B** contours are shown in Figure 6. The south-trending increase has been recognised previously (Barnett 1979). and was interpreted to be due to depletion of boron in the deep aquifer through steam separation since boric acid is slightly volatile. This explanation may be valid in the Upper Mahiao and Sambaloran sectors and is in line with the south-trending decline in gas described above. Subsequently, **it** has been found that the greatest **Cl/B** increase is across the Malitbog sector where **Cl/B** tends to approach the Bao Spring **Cl/B** ratio of **32.** Since the Malitbog reservoir is considered largely single-phase some other explanation must be invoked. The **Cl/B** ratio is often used to indicate the homogeneity of a geothermal reservoir since **it** is often similar to the ratio in the major aquifer rock type (Truesdell 1975) and should change **little** with subsequent

Figure 6: Molecular **Chloride/Boron** Ratio Contours

Figure 7:
DEEP AQUIFER CHLORIDE CONCENTRATION (mg/kg) VERSUS $\delta^{18}O$ (‰)



dilution. The upper Mahiao Cl/B ratio is consistent with a diorite rock type but the range of rock type observed across the field is not sufficiently marked to explain the Cl/B trend. The increase across the Malitbog and Sambaloran sectors and towards the Bao Springs may be due to loss of boron into the lattice structures of alteration clay minerals (Harder 1961).

STABLE ISOTOPE DATA

Water samples from rivers, hot springs and wells have been collected over the last 5 years for oxygen-18 and deuterium stable isotope analysis and this is more fully reported elsewhere. (Cope, et al. 1982). Tongonan geothermal fluids exhibit a maximum positive $\delta^{18}O$ shift of approximately 5.0‰ relative to the local meteoric water line; (the wells showing the greatest shift are 410, 407, 401, 209A) however the fluids have a higher deuterium content than local meteoric waters, (approx. 10‰ enrichment).

The deuterium enrichment of geothermal fluids with respect to local meteoric waters has been observed in other geothermal systems (Truesdell, et al. 1977) and has been explained in terms of subsurface boiling and dilution processes. For the purposes of this paper, a plot of aquifer chloride vs $\delta^{18}O$ has been constructed; Figure 7. Calculated aquifer chloride values have been used instead of total discharge chloride for wells with excess enthalpy except for well water samples that have obviously suffered dilution by either meteoric water (e.g. 402 (1), 202 (1) or drilling fluids (501). This is considered to be justified on the basis that steam separation which has occurred in the reservoir at temperatures above approximately 280% (subsequently diluting the well discharge) will result in very little isotopic fractionation.

From Figure 7 two dilution lines have been drawn. The dilution line which passes through the Bao Valley thermal fluid composition supports the view of fluid flow to the Bao Valley via the western Malitbog, but the dilution water probably does not have the $\delta^{18}O$ composition (-3‰) implied by the line. The relative enrichment of Bao Valley thermal fluids in ^{18}O with respect to local meteoric water may be influenced by steam separation at temperatures of around 220°C and the diluting water is probably local meteoric water of composition; $\delta^{18}O$ -5.5‰ and 6D; -6.5‰.

Some wells appear to be diluted by a water of isotopic composition; $\delta^{18}O$; -5.5‰. and δD; -30‰ which corresponds to the parent water for the geothermal luids (in which no deuterium shift has occurredf but no local meteoric water with this isotopic composition has yet been found.

STRUCTURAL PERMEABILITY

Figure 8 shows the Tongonan field with thermal springs (Baltasar, et al. 1982), fault traces and probable reservoir flow paths. The geochemical, field trends have delineated the proposed major flow paths and some structural control of hydrology is evident. A consideration of the permeability of these structures is necessary in assessing their hydrological importance.

Primary permeability in the andesite and diorite rocks is low and fluid is believed to move through fractures formed by tectonic movement along faults and through intrusion of the diorite pluton. The present permeability of faults appears to vary greatly throughout the Tongonan field. Along the Central Philippine Fault low permeability due to

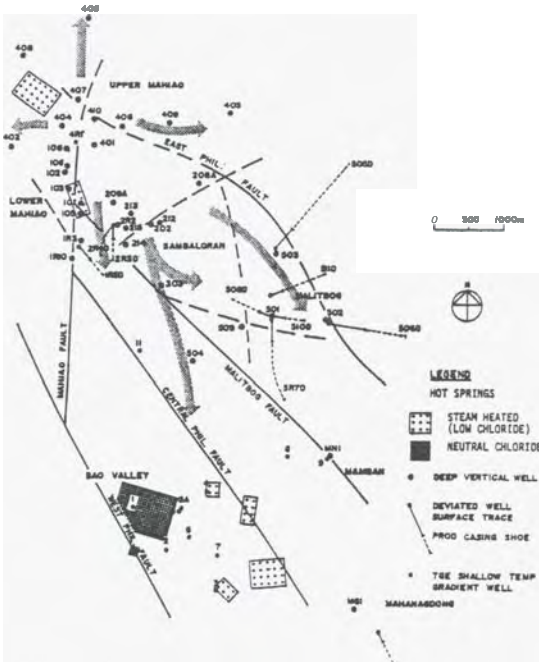


Figure 8:
PROBABLE HYDROLOGICAL FLOW DIRECTIONS IN TONGONAN RESERVOIR (SHOWN AS SHADED ARROWS -)

clay formation was observed in Well 1R10 and this evidence together with the low output of Well 402 has discouraged exploration west of this fault. However, vertical electrical soundings west of the Central Philippine Fault suggest low resistivity at depth and a possible hydrological connection with the Tongonan system (Bromley, C.J. pers. corn. 1982). Wells 408 and 505D were found to be largely impermeable due to extensive silicification which has sealed fractures.

Good permeability is seen where spring activity is aligned along fault traces, for example, the Bao Springs along the West Philippine Fault. Permeability in the Malitbog sector appears related to younger splinter faults while the unusually high gas concentrations in Well 511D may be derived through permeable channels in the East Philippine Fault.

Although the Upper Mahiao region is considered to be the major upwelling zone in the Tongonan field, permeability (measured by injectivity during well completion tests) is not as high as that seen in the Sambaloran sector. However lower reservoir permeability is partly compensated for by the higher fluid temperatures which give water a lower viscosity. The Upper Mahiao wells also have lower total mass flows compared with Sambaloran wells. This is partly due to the higher enthalpies in the Upper Mahiao sector and the associated lower effective mass flux of steam through the reservoir compared to water.

CONCLUSIONS

Consistent field trends in geochemical parameters have been used to delineate probable hydrological flow paths in the Tongonan reservoir. The Upper Mahiao sector is seen to exhibit highest reservoir temperatures and mineralization and is considered the principle upwelling zone in the Tongonan field.

Dilution and cooling trends have been recognized in all directions away from the Upper Mahiao sector and for the deep wells so far drilled mineralization is lowest on the southern periphery of the Malitbog sector. The major outflow to the Bao Valley springs is considered to be derived largely from the western Malitbog area and possibly the Lower Mahiao.

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