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The Hydrological Model of *the* Mahanagdong Geothermal System

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Abstract

The Mahanagdong sector of the Leyte Geothermal Power Project (LGPP) is committed to supply 180 MWe of steam by mid-1997. An updated hydrological model was carried out based on available geoscientific and reservoir engineering data from a total of 34 wells drilled in the area. The Mahanagdong resource is derived from a fracture-controlled and volcano hosted geothermal system characterized by neutral to slightly alkali-chloride fluids with resenoir temperatures exceeding 295°C. A major upflow region was identijied in the vicinity of MG-3D, MG-14D and MG-5D. Fluids outflowing io the north possibly encountered an acid body originating from condensed magmatic HCI-rich vapors or a sulfur-rich body producing acid Cl-SO_4 fluids. Isochemical contours indicate outflowing fluids with temperatures of 270-275°C to the south and west. Its southwesterlyflow is restricted by the intersection of the impermeable Mahanagdong Claystone near MG-10D, which delimits the southern part of the resource. Low chloride, shallow inflows are evident at the west near MG-4D and MG-17D wells which act as a cold recharge in this sector.

INTRODUCTION

The Mahanagdong sector **is located within** the Leyte-A Geothermal Field, **southeast** of the **existing 112.5** MWe **Tongonan-1** Power Plant. **Committed** to **supply** 180 MWe of ***steam*** for the **mid-1997 commissioning** of the **440** MWe Leyte-Luzon **grid** interconnection, the sector is divided into the Mahanagdong-A **and** Mahanagdong-B power development **sectors.** These two developments are undergoing construction with separate power plants **having** capacities of **120** MWe **and** 60 MWe, respectively. To date, a total of **34** wells have been drilled in the sector, **24** for production and **10** for reinjection purposes, including 3 reinjection wells **on** the adjacent **Mamban** block (Fig. **1).**

The Mahanagdong-A development is well **within** attainment of its target ***steam*** requirement of **120** MWe. Further drilling **activities on pad MG-RD1 are** expected to supplement the existing **balance** reinjection **capacity** for Mahanagdong-A which **total** 664 **kgls.**

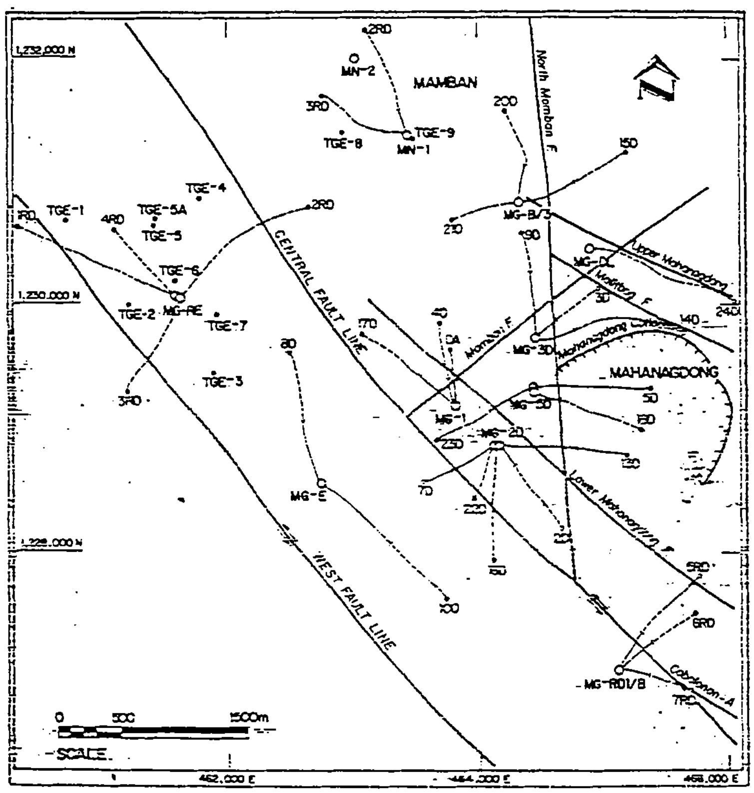

Figure **1: Location map** of Mahanagdong Geothermal Project

Mahanagdong-B on the other hand, with its planned 60 MWe plant capacity, was originally programmed to utilize steam from production pad MG-B3. But after drilling three wells on the pad these wells revealed an acid-sulfate type of discharge fluid. The source for the 60 MWe steam requirement therefore, has became a major concern.

This study deals with the conceptualization of a hydrological model for Mahanagdong based on geoscientific and available reservoir engineering data. The conceptual model will identify the upflow, recharge and outflow areas and the distribution of acid fluids correlated with subsurface structures in the area. Such information will be valuable in future drilling strategies for reinjection and production for the Mahanagdong-B development.

STRATIGRAPHY

Basement Complex (BC)

The oldest rock unit in Mahanagdong consists of metamorphic and ultramafic rocks such as serpentinite, serpentinized peridotites, hornblendites and hornblende diorites. A pre-Tertiary age is inferred for this chaotic assemblage based on correlations with basement rocks from established stratigraphic columns of other areas such as Mahagnao, Biliran Island and Calubian Peninsula, all in Leyte province. Wells MG-1RD, MG-3RD and MG-4RD all penetrated this formation and encountered no inherent permeability.

Mahiao Sedimentary Complex (MSC)

Overlying BC is the Early Miocene Mahiao Sedimentary Complex (MSC) .composed of sedimentary breccias and conglomerates with clasts of microdiorite, quartz monzodiorite and minor andesites and dacites set in a fine-grained sandy to clayey groundmass. This formation was earlier regarded as a plutonic unit and named as the Mahiao Plutonic Complex. Examination of the cores cut in wells MG-1, MG-17D and MG-2RD however, showed a sedimentary matrix holding together the plutonic fragments.

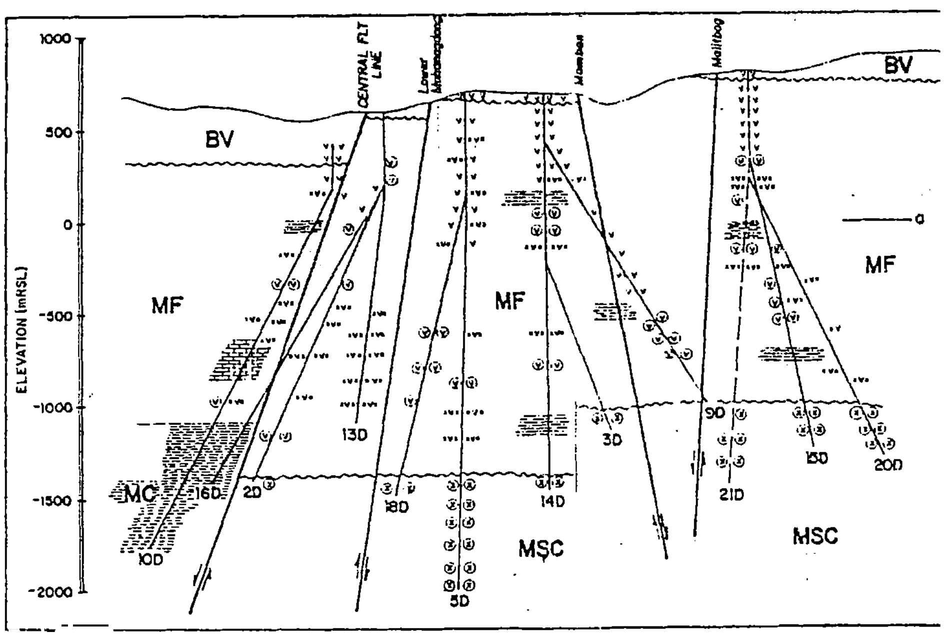

Figure 2: Stratigraphy of Mahanagdong

Previous logs of cores and petrographic analysis of thin sections may have failed to distinguish the sedimentary nature of the matri.. due to intense alteration. This is especially true in cores retrieved from wells in Upper Mahiao sector. In the Mahanagdong sector, the fragmental character of the intrusives was apparent in the less altered sedimentary cementing material.

Mahanagdong Claystone (MC)

Here considered as a distinct stratigraphic unit from the Early Miocene Mahiao Sedimentary Complex is the Mahanagdong Claystone. This formation was intersected by wells MG-10D and MG-2RD and some other wells towards the northwestern and western edge of the geothermal field. This is composed mainly of claystone, siltstone and sandstone with minor conglomerates, limestone and chert. The dominating claystone unit is made up of minute clay and carbonaceous laminations. Although dissected by a large number of structures, this thick clastic formation appears to be inherently impermeable.

It is believed that the Mahanagdong Claystone was formed later than the reworked Middle Miocene clasts of limestone within its conglomeratic unit, making it much younger than the Early Miocene Mahiao Sedimentary Complex. It is possible that this formation represents the unconformable contact between the Mahiao Sedimentary Complex and the Mamban Formation east of the Central Fault Line.

Mamban Formation (MF)

Chronologically younger than the MC is the Mamban Formation (MF). This consists of andesite lavas, hyaloclastites and tuff breccias, with occasional interbeds of fine grained clastics such as sandstone, siltstone, claystone and fossiliferous limestone. The presence of the sedimentary lenses provides proof of its submarine origin during the early stages of volcanism in the area. Paleontological dating of carbonate cores from MN-1 in Mamban suggests a Late-Miocene to Pliocene age and a bathyal environment of deposition.

Bao Volcanics (BV)

Surface rocks in the Mahanagdong sector are dominantly composed of fresh to weakly weathered andesite lava flows intercalated with pyroclastics of the BV. A paleosol separates the overlying BV with the MF. They are considered age equivalents of the Sambaloran volcanics in the north of which a Plio-Pleistocene age is assigned.

This formation was used to be called different names according to the sector or area where it was encountered, with names such as Cabungagan Volcanics, Sambaloran Volcanics and Mahanagdong Volcanics. But due to the general agreement on the composition, description and likely age of these numerous Quaternary lavas and volcaniclastic units, the assignment of one encompassing formation unifies the stratigraphy of the GTGF.

West of the Mahanagdong area bounded by the Central Fault line, exposures of pyroclastics and related deposits consisting of water-laid and airfall andesitic tuff, breccias and lahars are observed near the confluence of three major river systems in the Bao Valley. These deposits comprise the North Central Leyte Formation (NCLF) which measure 580 m in thickness and were encountered by most shallow TGE wells.

HYDROTHERMAL ALTERATION AND TEMPERATURE

In Tongonan Geothermal Field, mineral alterations are correlatable with the prevailing formation temperature. In case of Mahanagdong, mere replacement of the original minerals have been proven ineffective in predicting the downhole temperatures. A study conducted by Zaide-Delfin and Dulce (1995) on hydrothermal trends in Mahanagdong indicated that the distribution of replacement minerals (e.g. clays and epidotes) were generally inconsistent with the present downhole temperature. They concluded that the replacement minerals in the sector are relict and therefore, should not be used as mineral geothermometers. Likewise, the simple use of the usual index acid minerals have lately been unsuccessful in predicting the presence of active acid fluids in the wells.

However, most of the vein minerals studied were predominantly unaltered and reflect the measured downhole temperatures. The vein minerals in Mahanagdong represent the most recent system and therefore, should be used in predicting the stable formation temperatures of wells drilled in the sector.

The vein mineral geothermometers and stable formation temperatures were combined to determine possible fluid flow directions in Mahanagdong.

Figure 3 is an isothermal plot based on vein mineralogy and fluid inclusion along a north-south section while Figure 4 is the isotherms of stable measured temperatures plotted on the same cross-section. Figures 5 and 6 are isotherm contours at -1000mRSL using vein mineralogy and downhole measurements, respectively. These plots indicate a reasonable agreement between vein mineralogy and measured downhole temperatures.

The plots demonstrated that the area drilled by wells MG-3D, MG-9D, MG-5D and MG-14D represents the hottest sector of the field. This is strongly evidenced by the shallowest first occurrence of epidote veins (≥240°C), the presence of actinolite veins (≥260°C) and secondary biotite veinlets (≥280°C). On the other hand, the downhole measurement data showed that the 300°C temperature contour is similarly shallow in wells MG-9D (-800mRSL), MG-3D (-1000mRSL), and MG-5D (-1500 mRSL).

At the south, the plunge in depth of occurrence of epidote veins, the disappearance of high temperature minerals and the decrease of stable formation temperatures in wells MG-2D and MG-16D, suggests that these wells were drilled close to the margin of the geothermal resource.

Further southwest, in the area defined by wells MG-8D and MG-10D, a meager hydrothemal alteration is observed This indicates a very limited fluid flow due to very tight permeability of the Mahanagdong Claystone formation that characterize this sector of Mahanagdong.

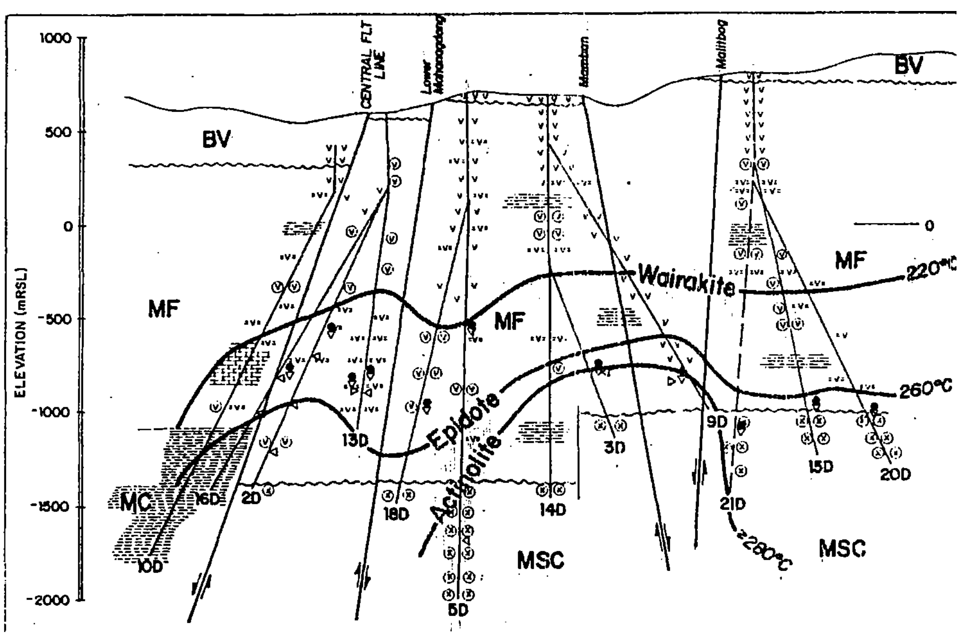

Figure 3: Isotherms based on Vein Mineralogy and Fluid Inclusion

The isotherms also indicate that wells MG-1, MG-2D, MG-7D, MG16D, MG-19, MG-5D, MG-18D, MG-13D and MG-15D intersected hot fluids with temperatures of more than 270°C at -1000mRSL. These fluids conspicuously originate from the hot sector in the vicinity of MG-3D, MG-14D and MG-9D. The relatively narrow elongated shape of isotherms defines a structurally-controlled flow towards southwest, south and southeast en route to Cambantog area.

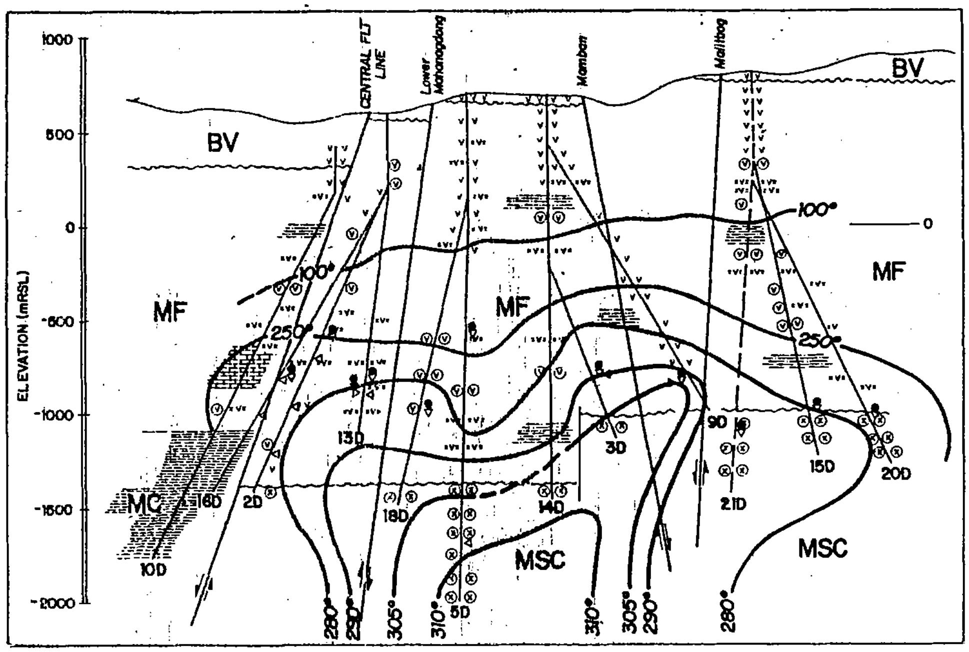

Figure 4: Isotherms based on Stable Measured Temperatures

In the western Mahanagdong sector, close to Paril dome, a relatively high temperature vein minerals of subhedral to euhedral epidote veins and high fluid inclusion homogenization temperatures were identified in the deeper sections of wells MG-4D and MG-17D. In addition, secondary biotite veinlets, which normally occur at temperatures of approximately 300°C, was noted in MG-17D.

However, these apparently high temperatures were not confirmed by downhole measurements. The relatively low maximum temperatures of 230°C and 241°C were measured in wells MG-4D and MG-17D, respectively. In MG-4D, the wide difference is caused by the strong downflow of cooler fluids from the upper permeable zone which masked the deeper true formation temperatures. However, the same can not be claimed for MG-17D where the measured temperature profile showed a distinct reversal which imply that the biotite veinlets are not recent.

The big discrepancy may indicate a very recent cooling trend due to the strong inflow of cool fluids from the west. This possibly forms part of the natural recharge of the Mahanagdong geothermal system.

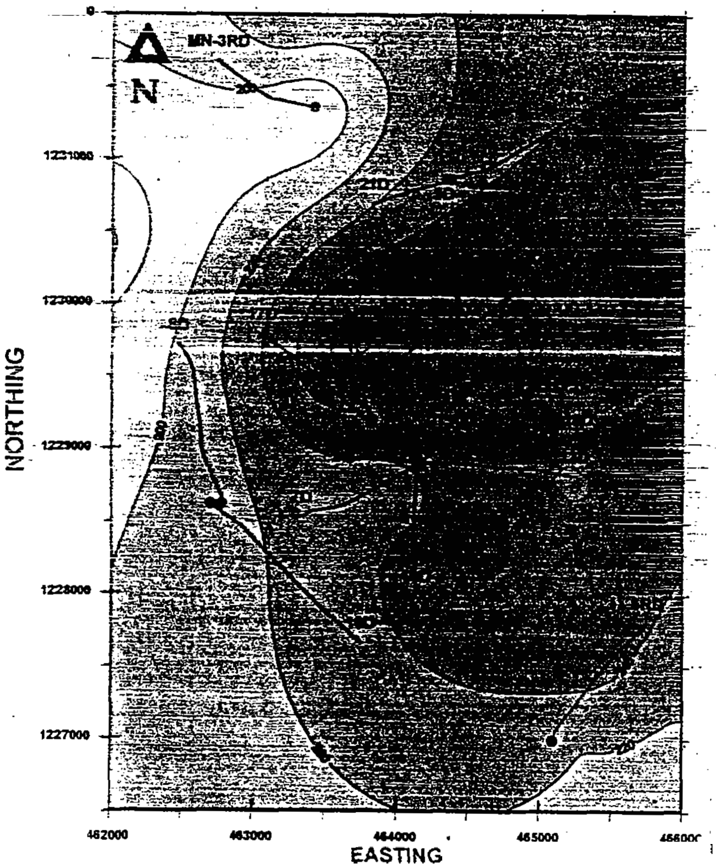

Figure 5: Isotherms at -1000 m RSL based on vein mineralogy

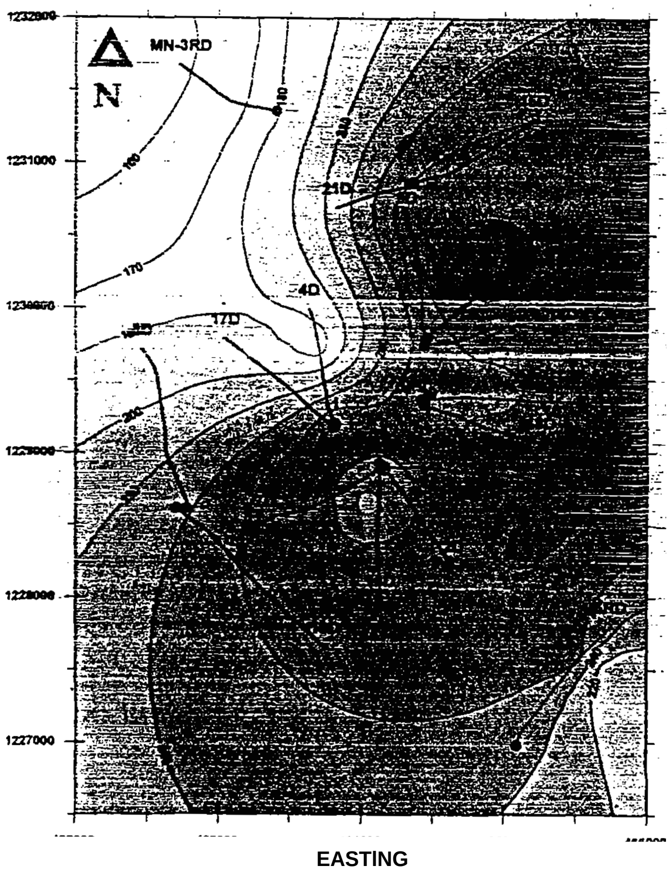

Figure 6: Isotherms at -1000 m RSL based on stable downhole measurements

CHEMISTRY OF MAHANAGDONG WELLS

The comparative average discharge chemistries at full bore condition are given in Table 1.

RESERVOIR CHEMISTRY AND FIELD TRENDS

Silica Geothermometry

The highest temperature of 290-295°C are observed in wells MG-9D, MG-3D and MG-14D, indicating its relative proximity to the major high temperature, upflowing fluid. Slightly lower quartz equilibrium temperature of 270-0275°C is noted in well MG-5D and MG-18D. However measured temperatures at the bottom recorded temperature of 310°C and 280°C, respectively which suggests the mixing with slightly lower temperature fluids from a shallow feed

TABLE 1. AVERAGE AND SELECTED CHEMISTRY DATA OF MAHANAGDONG WELLS AT FULL-BORE DISCHARGE CONDITION

WELL	H	pH	Cl res	Cl/B	TSiO2	CO2 TD	CO2/H2S
	kJ/kg	@ 25°C	mg/kg		°C	mm/100m	
MG-1	1276	7.88	2755	21	270	214	159
MG-2D	1150	8.16	2767	21	266	121	83
MG-3D	2500	7.40	4175	45	290	1052	45
MG-4D	830	8.28	1414	24	193	117	243
MG-5D	1410	7.86	2802	23	272	1231	300
MG-7D	1365	7.93	2690	21	274	183	67
MG-9D	1400	2.41	4364	99	295	143	16
MG-10D	2450	6.90	2530	0.8	226	7107	256
MG-13D	1390	8.31	3012	23	290	189	32
MG-14D	1790	7.74	3918	37	294	819	70
MG-15D	1370	3.80	3503	93	284	338	35
MG-16D	1170	8.02	2255	27	272	115	23
MG-17D	1035	8.25	2000	24	240	128	81
MG-18D	1210	8.60	2300	23	271	287	87
MG-19	1330	8.20	2767	22	275	220	49

Table 1: Average and selected chemistry data of Mahanagdong wells at full-bore discharge condition.

The silica temperatures decrease towards the south and west with values ranging from 270-275°C indicating a broad fluid outflow towards *this* direction (Fig. 7).

The lowest **silica** temperature values are recorded in wells MG-4D and MG-17D (190° and 235°C). These wells were drilled towards the northwestern part of the field and are highly affected **by** the strong inflow of cool fluid The tongue of low temperature contour ***suggests*** the presence of a cold recharge in **this** sector possibly channelled **by** the Mamban Fault, **E-W Paril** and Lower Mahanagdong faults.

A broad ouflow is postulated **to** the south-Southwestern **part** of the field towards MG-10D where **quartz** geothermometer indicate temperature of 220-240°C. **This** well appear to form the southwest **boundary** of the Mahanagdong resource which showed non-commercial wellhead pressure; low output, and increasing enthalpy (2630 kj/kg) due to its poor permeability.

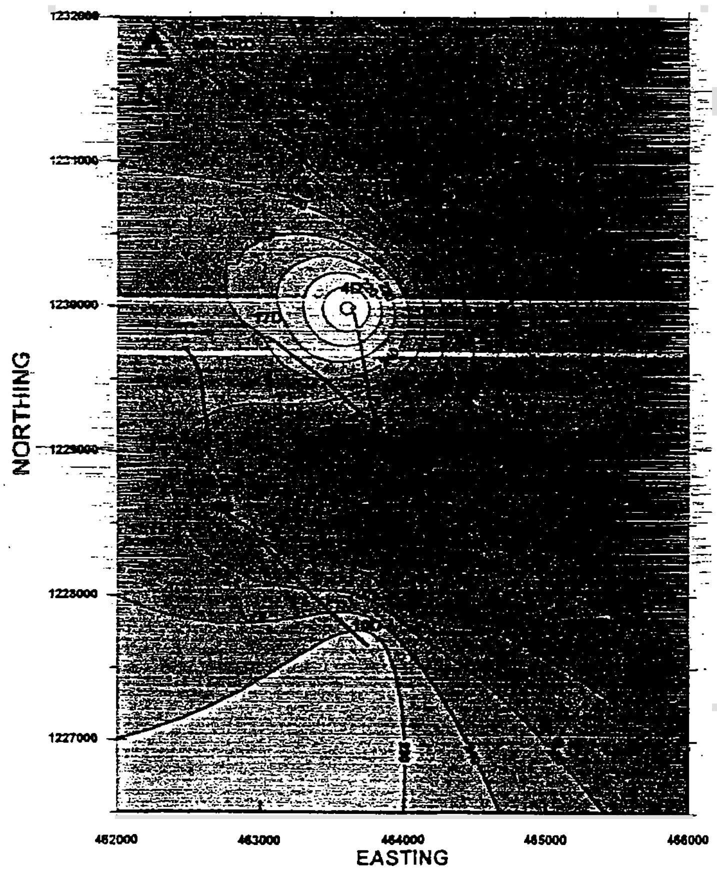

Figure 7: Mahanagdong iso $TSiO_2$ field contour

Reservoir Chloride

Reservoir chloride (Clres) values in total discharge in Mahanagdong wells is presented in Figure 8. Results show that the highest Clres (3600-4400 mg/kg) are exhibited **by** wells drilled northeast of the field **This** includes wells MG-9D, MG-3D and MG-14D and possibly MG-15D (3,6004,400 mgkg) where Clres was based only **on** a 6 days discharge. **This** *suggests* **this** region is tapping fluids most likely representing the central reservoir fluid **body** or drawing fluids which have extensively boiled.

Towards the south and west from wells MG-9D, MG-3D, MG-14D and MG-15D, reservoir chloride decrease significantly to 2,000 mgkg in **MG-17D/MG-4D** and 2,800 mg/kg in MG-16D. The 2,800 **mg/kg** chloride contour line extend up to MG-5RD located **south** of MG-13D based on its initial water chemistry during its 10 hour discharge tests.

The significant decrease in chloride contours **seen** in MG-4D and MG-17D (1,400-2,000 mgkg) indicate that these wells could have intersected a major zone of cold recharge into the central and southern sectors of the Mahanagdong field.

Cl/B Field Trends

The **Cl/B** ratio distribution is shown in Figure 9. A narrow range of 21-24 is exhibited **by** wells located in the central **part** of Mahanagdong; MG-1, MG-2D, MG-5D, **MG-7D,** MG-4D, **MG-13D,** MG-17D MG-18D and MG-19. This ***suggests*** a homogenous geologic environment. **The** Cl/B ratios show a **strongly** increasing trend towards the **north.** Wells MG-9D and MG-15D showed values of 90-97 and MG-14D and MG-13D gave values of 37 and 45. The high **Cl/B** ratio are believed to be due to the input of **an** undiluted **high** temperature parent **fluid** The overall Cl/B ratio field trend shows a decrease from the inferred upwelling zone towards the center and northeastern edges of the field

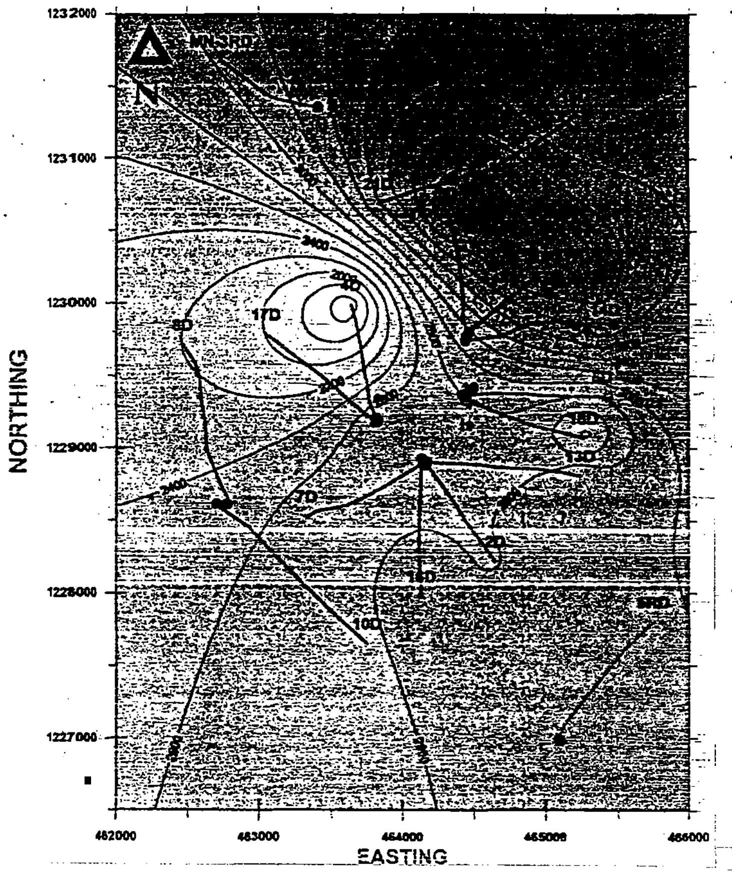

Figure 8: Mahanagdong iso Cl_{res} field contours

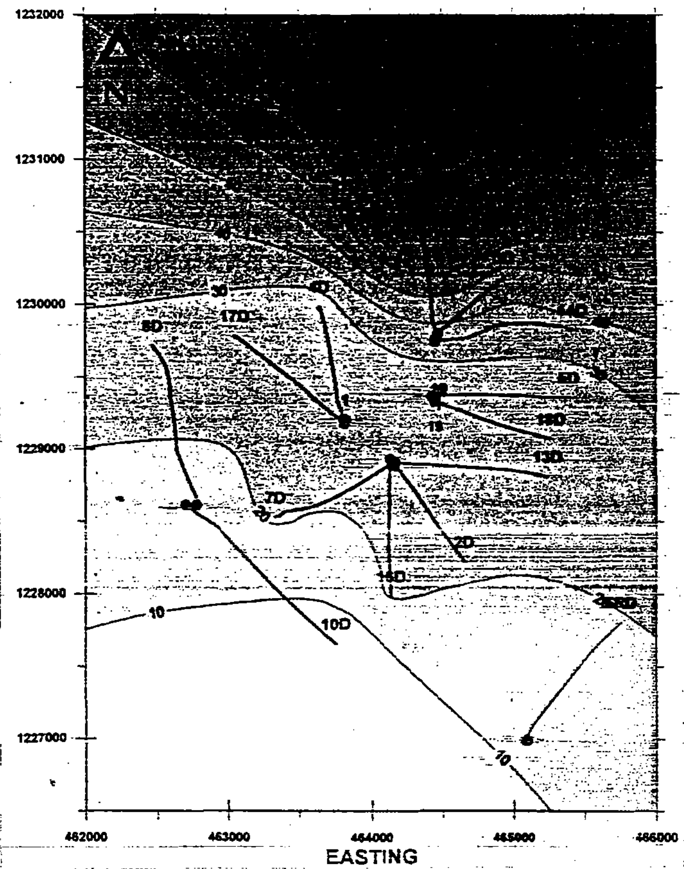

Figure 9: Mahanagdong iso Cl/B ratio field contours

Well MG-10D however, Cl/B ranges from 0.8 to 1.2 which is the lowest is Mahanagdong. This low Cl/B ratios is due to its high absolute boron concentrations due to a thick sedimentary unit encountered by the well or due to the highly two-phase nature of the discharge fluid where a significant fraction is boron-rich *steam* condensate.

WELL GAS CHEMISTRY

Table 2 presents the non-condensible gases of well discharge fluids at total discharge conditions. The major gas component is CO_2 with minor amounts of H_2S and NH_3 and residual gases (H_2, N_2, *Ar* and CH_4).

The highest CO_2 concentrations are noted in wells drilled towards the eastern part of the field where temperature and chloride were highest. CO_2 in total discharge is highest in well MG-5D with an average value of about 1230 mmoles/100 mole or 3.0 percent by weight in total discharge (Fig. 10). High gas concentrations were also noted in wells MG-3D and MG-14D with values from 800-1050 mmoles/100 mole in total discharge (2.0-2.6 percent by weight). High gas levels in MG-3D and MG-14D are noted at fullbore conditions and are attributed to the intersection of the Malitbog fault near bottom. The high *gas* levels in wells MG-3D, MG-5D and MG-14D are believed to originate from a gas-rich , two phase fluid and not from a natural gas zone.

The CO_2 contours exhibit **an** overall ***steep*** gradient towards the south and west decreasing tenfold over a relatively short aerial distance. This implies gas exsolution upon boiling **near** the upflow and decreasing gas towards the outflow.

TABLE 2. GAS CHEMISTRY IN TOTAL DISCHARGE AND GAS RATIOS, MAHANAGDONG WELLS

WELL	DATE	BPP	WHP	H	SP	CO2	H2S	NH3	N2	H2	CH4	Ar	He	CO2/ H2S	CO2/ NH3	CO2/ H2	CO2/ N2	CO2/ CH4	H2/ CH4
			MPaa	kJ/kg	MPaa	mmoles/100 moles in Total Discharge													
MG-1	1-Jun-81	FB	1.20	1266	1.13	226	1.0	-	-	-	-	-	-	238	-	-	-	-	-
	26-Apr-81	B6	3.11	1202	0.61	222	1.6	0.68	-	-	-	-	-	136	358	-	-	-	-
MG-2D	14-Nov-81	FB	1.21	1093	1.21	116	1.1	0.29	-	-	-	-	-	102	408	-	-	-	-
	9-Oct-82	B1	2.64	1076	0.42	119	1.6	0.39	1.96	0.03	0.24	-	-	81	303	3617	61	601	0.14
MG-3D	16-Sep-92	FB	1.43	2086	1.25	1136	24.7	4.07	6.46	1.36	0.60	-	-	46	279	841	208	1892	2.26
	2-Dec-92	B4	6.78	1680	0.72	628	13.6	3.15	60.94	18.70	6.06	-	-	46	200	34	10	104	3.00
MG-4D	26-Nov-90	FB	0.12	812	0.12	118	0.6	0.27	4.76	0.10	0.68	-	-	216	428	1196	24	201	0.17
MG-6D	19-Aug-83	FB	0.63	1280	0.64	1842	4.4	0.97	6.92	0.60	6.68	-	-	422	1894	3697	311	281	0.09
	17-Oct-83	B2	2.20	1090	0.83	1224	3.6	0.74	-	-	-	-	-	342	1644	-	-	-	-
MG-7D	18-Jan-91	FB	1.14	1366	0.43	226	4.1	0.42	1.41	0.05	0.33	-	0.009	56	636	4363	180	691	0.16
	13-Jun-93	A*	3.26	1003	0.66	123	2.7	0.26	0.47	0.05	0.38	-	-	46	499	2326	364	321	0.14
MG-9D	26-Apr-94	FB	1.87	1400	0.48	146	8.8	0.02	4.59	0.03	0.24	0.020	-	17	9000	4878	32	617	0.13
	11-Mar-96	B3	3.44	1160	1.04	102	6.9	0.01	0.62	0.24	0.13	-	-	17	7686	423	196	787	1.86
MG-10D	9-Mar-94	FB	0.17	2486	0.17	6109	22.1	10.29	0.49	0.02	17.16	-	-	276	594	326623	12377	356	0.002
MG-13D	9-Nov-94	FB	0.97	1392	0.60	191	5.6	0.76	-	0.18	0.94	-	-	34	256	3120	-	681	0.19
	29-Oct-94	B6	4.12	1327	0.47	196	6.9	0.91	0.02	0.07	0.41	-	-	33	217	2863	10492	474	0.17
MG-14D	16-Aug-94	FB	0.73	1764	0.60	769	12.0	4.11	1.43	1.13	0.82	-	-	64	187	680	536	937	1.22
	8-Aug-94	B4	3.79	1289	0.42	449	6.1	2.54	0.44	0.09	0.76	-	-	73	177	5181	1021	588	0.11
MG-15D	17-Dec-94	FB	0.96	1314	0.84	269	10.0	0.05	2.06	0.38	1.26	-	-	26	5208	710	126	206	0.29
	18-Dec-84	B2	2.64	1199	0.94	206	11.3	0.01	0.89	0.48	0.51	-	-	18	18680	430	230	404	0.94
MG-16D	27-Oct-94	FB	0.70	1183	0.42	96	3.1	0.36	0.18	0.02	0.06	-	-	31	264	5900	541	1763	0.30
	22-Sep-94	B2	2.66	1101	0.64	108	3.2	0.21	-	0.01	0.04	-	-	34	516	8362	-	2701	0.29
MG-17D	14-Nov-94	FB	0.66	1039	0.62	128	1.6	0.26	0.48	0.01	0.23	-	-	82	497	10964	267	548	0.03
	8-Dec-94	A2	1.01	1028	0.37	122	1.7	0.32	0.38	0.01	0.22	-	-	71	386	16722	324	564	0.03
MG-18D	17-Jan-95	FB	0.91	1193	0.69	308	3.0	0.60	0.79	0.04	0.37	-	-	101	512	8046	396	838	0.10
MG-19	2-Jan-95	FB	1.22	1322	0.97	216	[illegible]	1.16	0.88	0.03	0.37	-	-	49	186	6634	244	686	0.09
	12-Jan-95	B2	2.88	1238	1.23	202	3.9	0.40	0.66	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

NOTES:
BPP : Back Pressure Plate
WHP : Well Head Pressure
H : Enthalpy
SP : Sampling Pressure

Table 2: **Gas** chemistry of Mahanagdong wells in total discharge and gas ratios.

A localized **high** non-condensible gas levels (97,000-15,900 mmole/100 moles or 24-39 percent **by** weight) is observed in MG-10D **and** is believed to be a pocket of *gas* rich, **highly** two phase condensate layer that **has been** separated within a formation of limited permeability.

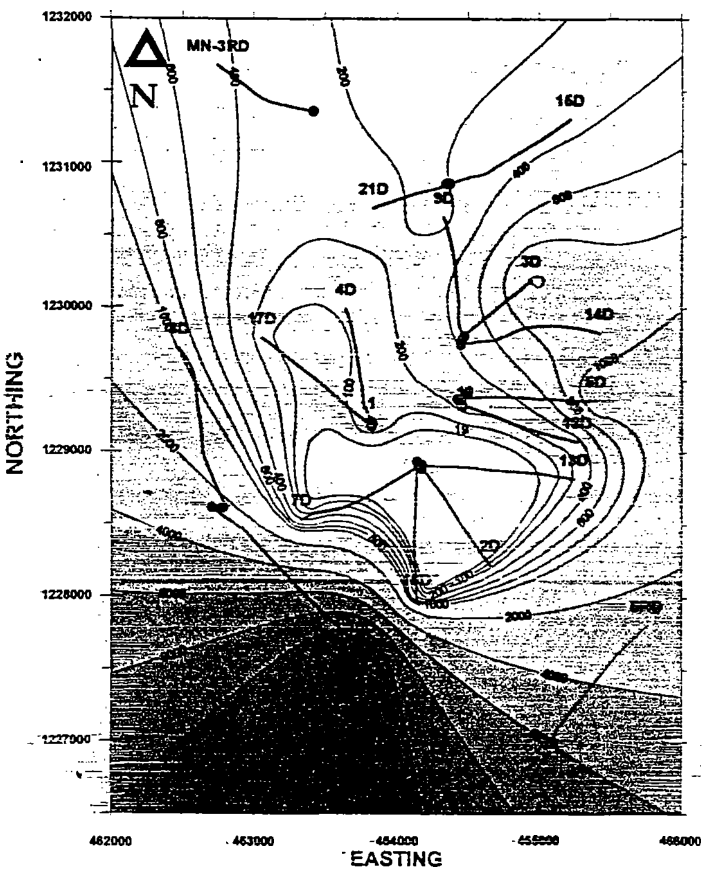

Figure 10: Mahanagdong **iso** CO_{2TD} field contours

ACID FLUIDS

Acid minerals are also present in Mahanagdong, however, they do not correspond well with the discharge chemistry of the wells. For instance, fresh alunite minerals regarded as an indicator of acidity, are sometimes present in neutral wells but absent even in wells that produce acid fluids. Wells MG-3D and MG-14D discharged neutral-pH fluids despite the presence of alunite and diaspore crystals. In MG-9D, except for the weak occurrence of alunite in the uncased section, the mineral was not observed in the confirmed acid permeable zones.

One interesting detail worthy of attention is the spatial distribution of acid wells in Mahanagdong. Wells with confirmed acid discharge chemistries are MG-9D, MG-15D, MG-20D and MG-21D. All the acid wells mentioned above were drilled either within or towards the northern region of Mahanagdong. These wells were accessed from pad MG-B3, with the exception of MG-9D which was drilled from MG-3D pad From this spatial relationship of the acid wells, an acid block seems to exist in the northern sector of Mahanagdong.

Chemical analyses of acid fluid samples from these wells show distinct chemical characteristics against the typical neutral chloride wells (Table 3) such as (1.) higher Cl/B ratio of 63-104 (2.) lower CO_2/H_2S ratio 7-26 (3.) high sulfate and (4.) high or comparable reservoir chlorides and quartz equilibrium temperatures relative to neutral wells drilled nearest the hottest part of the reservoir.

WELL	DATE	pHWBX	Cl res	SO4 res	Mg res	Cl/Ca	Cl/B	TSIO °C	TNaKCa °C	CO2 td	H2S td	CO2/H2S
			(mg/kg)							mmoles/100 moles H2O		
ACID WELLS												
MG-9D	26-Apr-94 A		4208	350	17.3	85	91	288	304	155	9.5	16.3
	26-Apr-94 B	2.41	4398	379	18.8	84	99	298	302	128	7.9	16.3
	26-Apr-94 C	2.41	4359	380	18.5	86	103	295	304	145	8.8	16.5
	10-Mar-95	5.06	4972	82	13.2	61	104	297	292	249	14.3	17.4
	11-Mar-95 A		4046	40	12.1	84	101	290	295	278	155.5	18.0
	11-Mar-95 B	3.47	4711	43	12.2	78	99	290	290	273	15.5	17.8
MG-15D	10-Dec-94	3.80	3402	75	7.0	119	88	286	286	209	11.3	18.2
	17-Dec-94 A		3474	81	7.4	99	92	282	284	189	9.1	20.8
	17-Dec-94 B	3.78	3505	84	7.9	106	93	286	287	258	10.0	25.9
MG-21D	11-Oct-95	3.43	3393	293	12.6	150	64	260	275	207	7.1	7.1
	12-Oct-95	3.30	3397	288	13.0	178	63	271	274	182	7.2	7.2
	13-Oct-95	5.43	3503	508	13.8	32	63	268	253	275	7.6	7.8
NEUTRAL WELLS												
MG-3D	16-Sep-92	7.74	3502	18	0.2	66	45	281	278	1130	24.7	46.0
	2-Dec-92	7.10	4204	9	0.1	63	45	284	290	620	13.6	48.0
MG-5D	19-Aug-83	8.04	1988	43	0.2	150	22	258	244	1042	4.4	422.0
	17-Oct-83	8.01	2202	68	0.1	189	24	260	250	1224	3.6	342.0
MG-14D	16-Aug-94	7.75	3070	82	0.2	333	37	204	297	708	12.0	64.0
	8-Aug-94	7.88	3740	27	0.1	406	40	202	302	440	0.1	73.0

Table 3: Comparative chemical parameters of acid and neutral wells in Mahanagdong-B.

The higher chloride to boron ratio is attributed to the significantly lower absolute boron concentration relative to the neutral chloride well fluids. This may be due to the input of magmatic fluids that is enriched in chloride but deficient in boron. In the gas phase, these acid wells exhibit lower CO_2/H_2S ratios than neutral wells due to higher absolute H_2S levels generated by magmatic gas intrusion or by sulfur hydrolysis based on the occurrence of sulfur in the upper 1200 m of well MG-24D.

CONCEPTUAL HYDROLOGICAL MODEL

Based on the chemistry, geology and well information data discussed, the upflow region in Mahanagdong field is delineated to be in the northeastern part of the field near the vicinity of wells MG-3D, MG-14D and MG-5D (Fig. 11). This is characterized by reservoir chloride concentrations of 3500 mg/kg, high temperatures of at least 290°C based on quartz equilibrium temperatures and stable downhole measurements, high gas Content and two phase inflows. The heat source driving the system is believed to be associated with episode of volcanism which brought about the formation of New Mahanagdong Volcano/Mahanagdong Collapse.

These fluids migrate to shallow depths through near vertical structures such as the Malitbog Fault and Lumpag family of faults. Wells drilled towards these sector such as MG-3D, MG-14D and MG-5D encounter high gas levels generated by the vertical exsolution of geothermal gases upon boiling near the upflow.

The outflow regions were identified towards the north, west, and southern part of the field defined by decreasing trends in temperatures, reservoir chloride and gas content with the outflowing fluid undergoing cooling and mixing towards these direction.

Towards the west, in the vicinity of wells MG-4D and MG-17D, isochemical contours show a sharp gradient indicating a discrete, structural control of cold meteoric recharge possibly channeled by the E-W Paril, Mamban and the Lower Mahanagdong Faults.

Towards the north, outflowing fluids mixed with a localized deep seated body of acid fluids which wells MG-9D, MG-15D and MG-21D have tapped. The mechanism of acid fluid generation is possibly associated with the condensation of magmatic HCl-rich vapors exsolved from a cooling magma or through the hydrolysis of sulfur. However the origin of these magmatic volatiles could not yet be established.

Towards the south, fluid flow is generally controlled by the Lower Mahanagdong Fault as the fluids assumes southeast flow towards Cambantog area.

The southwestern boundary of the resource is defined by well MG-10D based on fluid chemistry and geology. This well is characterized by low permeability, low temperatures and condensate type of discharge fluids. The high absolute boron concentration yield low Cl/B ratios which reflects a different geologic environment dominated by the impermeable (Mahanagdong Claystone) marine sedimentary rocks.

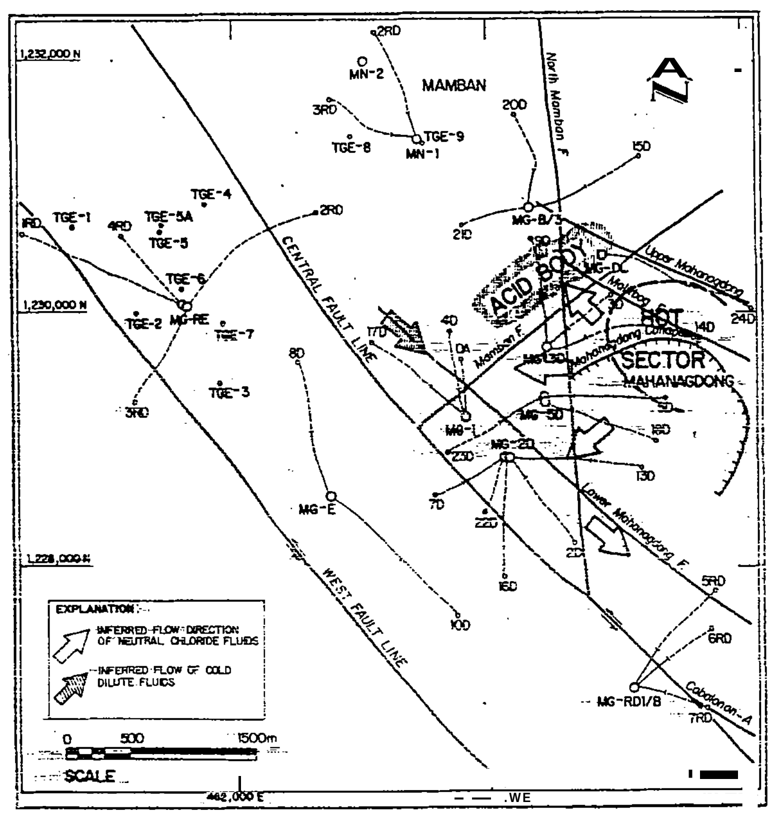

Figure 11: Postulated Hydrological flow path of Mahanagdong Geothermal System

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