HYDROTHERMAL MODEL OF MT. PARKER, A QUATERNARY VOLCANO IN SOUTH COTABATO BASIN, MINDANAO ISLAND, PHILIPPINES

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SUMMARY - Parker Volcano lies along the Sangihe volcanic arc, a Quaternary volcanic chain running from Sulawesi, Indonesia to Central Mindanao. The volcanic complex developed over the folded Miocene sediments of the South Cotabato Basin which are composed chiefly of limestone, and fine to coarse grained clastics. Volcanic deposits include dacite and andesite lavas, and very extensive pyroclastics. The major structural grain of the region runs northwest with a conjugate northeast trend.

Neutral sulphate springs and seepages effuse at Lake Maughan, the crater lake of Mt. Parker. It is apparent that the cold meteoric waters of the lake has a quenching and neutralising effects on the ascending hot gases beneath the crater region. The lake also act as the sink of gaseous constituents of the system as indicated by the high-sulphate level in the lake waters. Neutral chloride waters percolate along the structures around the volcano and spring out towards: Bungo in the southeast, Salvan and Bagong Silang in the east, and Islakit and Tinulang in the northeast. The close values of B/Cl ratios among these springs, from 0.015 to 0.023, indicate homogeneity of the fluid source and the presence of "andesitic" thermal system. The dilution trends of warm and hot spring models support the single-source of the fluids and give an estimate reservoir fluid temperature of about 230 to 250°C.

1.0 INTRODUCTION

Parker Volcano rests upon the southern edge of Cotabato Sedimentary Basin in Mindanao Island (Fig. 1). The Quaternary volcano lies next to Daguma Range in the west, Roxas Anticline in the north and Mt. Matutum in the northeast.

The Mines and Geosciences Bureau (MGB) initiated the geological surveys in Mt. Parker and Cotabato Basin (Santos and Baptista, 1963; MGB, 1982; Villamor and Muere, 1990). Regional and semi-detailed maps appear in the Geologic Map of the Philippines (1967) and on the Quadrangle Map of Polonoling (1990). Various sedimentological studies for petroleum prospecting, including drillholes, have been conducted in the northern portion of the basin (e.g. PNOC-EC, 1982; BED, 1986). Tectonic studies of the Molluca Sea Plate involving focal mechanisms of earthquakes have included the structures, volcanism and development of the Cotabato Basin (Hamilton, 1979; Cardwell et al., 1980; McCaffrey, 1982). On the other hand, there has not been any geochemical report on the thermal features in the area.

This paper presents the semi-detailed studies on the volcanism and geology of Mt. Parker Geothermal Prospect. This also include the results of the geochemical surveys of the thermal springs and alteration studies of the altered zones in the area. The integrated surface geology and geochemistry paved the way for the conceptualisation of the hydrothermal model in Mt. Parker.

2.0 GEOLOGY

2.1 Regional Setting

The Cotabato Sedimentary Basin (Fig. 1) covers an approximate area of 10,000 km^2 in soutwestern Mindanao. It is a northwest-trending basin containing Pre-Oligocene to Pleistocene stratigraphic units with total thickness of 5,000 to 8,500 m. Daguma Range bounds the west and southwest portions of the basin following the configuration of the Cotabato Trench. The Central Cordillera, a complex suite of uplifted Pre-Miocene and younger rocks, form the eastern margin of the basin.

A north-trending chain of Quaternary volcanoes encompassing Mts. Hibok-Hibok, Balingasag, Apo, Matutum, Parker and Balut runs parallel to the Central Cordillera. This volcanic chain appears to mark the northern extension of Sangihe arc which runs from the northern arm of Sulawesi to Sangihe Island, Indonesia.

Focal mechanisms of seismic activities have shown that the Sangihe arc is colliding with East Mindanao-Talaud-Halmahera arc in the east (Hamilton, 1979; Cardwell et al., 1980; MacCaffrey, 1982). Arc-arc collision was initiated before the Miocene which led to the inception of normal faulting in Cotabato Basin. The northwest-trending horst-and-graben features developed into a sedimentary basin from Miocene to present.

Interpretation of seismic zones have shown that the collision between Sangihe and Halmahera has gone to completion in Mindanao, but still in progress towards Celebes Sea in the south. It also indicated recent seismic events in Cotabato Trench which influence the present tectonism of the basin.

2.2 Stratigraphy

The Pre-Miocene rocks in Daguma Range represent the oldest rock units in the area. The rocks are composed of a variety of metamorphics, volcanics and intrusives. The contact of the basement rocks with the younger rocks marks the western limits of the Cotabato Sedimentary Basin.

An extensive sequence of folded Miocene sediments covers the basement in the basin, The oldest exposed sedimentary unit is the Early Miocene Lamhako Limestone, composed chiefly of basinal limestone with calcareous clastic intercallations. It is overlain by the siltstone, claystone mudstone and minor limestone of the Mid-Miocene Taluko Formation. The last of the Miocene sediments is the Late Mid-Miocene Lampari Formation composed of coarse clastics and tuffaceous sandstone and siltstone. All of the Miocene sedimentary units form the underlying rocks of the Roxas and Lamhako Anticlines, and extend beneath Parker volcanic deposits in the south.

Bluhal volcanics marks the top of the Miocene deposits. This andesite and basalt lava flows, as well as the Miocene sediments, is intruded by dacite to diorite Malibato Intrusives. Bluhal Volcanics and Malibato Intrusives crop out and host a vein-type mineralisation in Kematu, north of Mt. Parker.

The Pliocene Estaw Formation unconformably overlies the Malibato Intrusives. The sequence is typified by moderately folded coarse-grained and tuffaceous clastics.

The Pliocene-Pleistocene Parker volcanics capped the stratigraphic sequence of the area. Volcanic deposits are disposed around Lake Maughan, the crater lake of Parker Volcano. Two distinct volcanic episodes are indicated from the deposits. The early volcanic activity extruded mostly andesitic lavas with associated pyroclastics and domes. The younger episode emitted andesitic to dacitic lavas and dacitic pyroclastics northeast and east of Mt. Parker. The last eruptions are possibly of explosive-type, as suggested by the formation of a wide crater region, and the extensive fine pumice-rich pyroclastic deposits.

2.3 Structures

Fig. 2 shows the structures and the location of the thermal areas in Mt. Parker.

The northwest regional trend strongly influenced the structural grain in the Mt. Parker prospect. Fold axes of the Miocene sediments follow northwest orientation, as typified by the Roxas and Lamhako Anticlines.

The dominant fault set show a general northwest orientation sympathetic with the regional trend. The most dramatic of this set occurs near Daguma Range where normal fault-controlled Pre Miocene basement rocks in the west is in direct contact with Quaternary rocks in the east. Kematu and Butlihek Faults, believed to host a vein-type gold mineralization in Kematu, belong to this set. The structures chanelling thermal fluids at the crater region of Mt. Parker likewise trend northwest.

A second, less pronounced structural set strikes in a general northeast trend. This is exhibited by the Malibato, Salmotan and Basag Faults, as well as the fold axes of the synclines and anticlines in the Estaw Formation. This structural set is suspected to be a younger fault set.

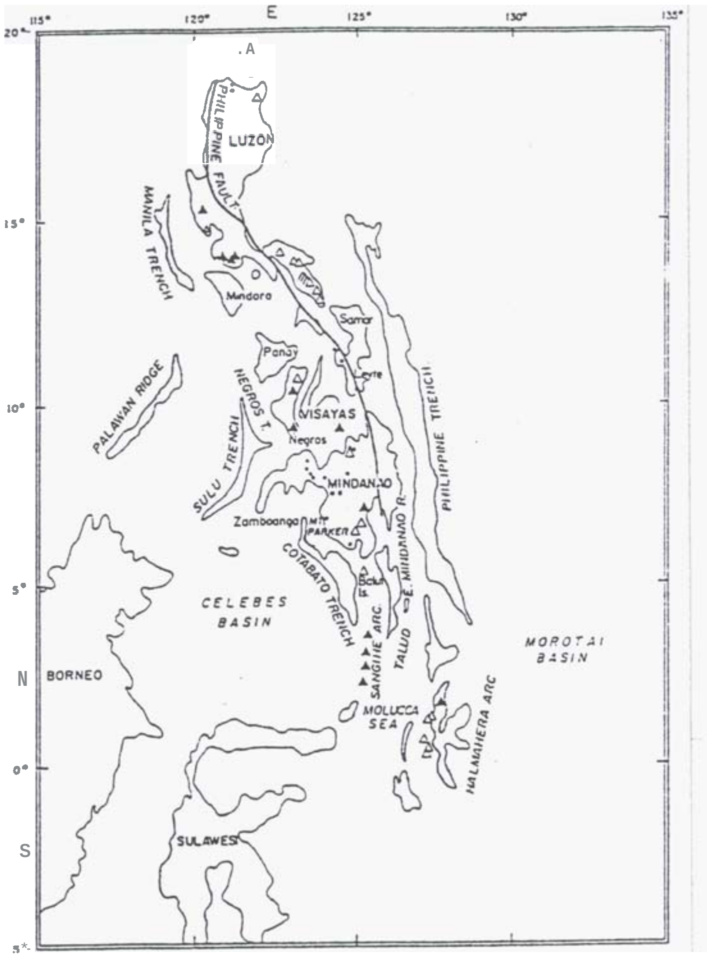

Fig. 1: Location map of Mt. Parker

The third fault group is localised and limited within the Lake Maughan vicinity. This set, represented by Bululfet and Asamblak Fault, strikes almost east-west, and is believed to channel thermal fluids in Lake Maughan. Most structures in Mt. Parker are concealed by thick pyroclastic deposits.

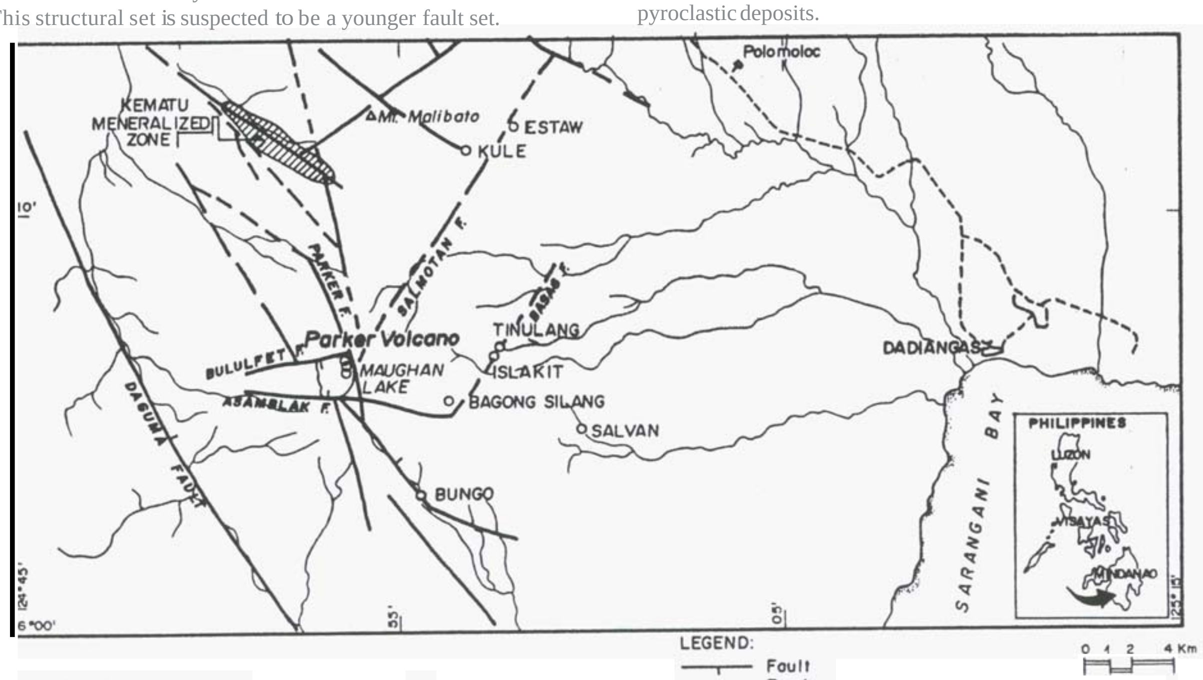

Fig. 2: Map showing structures and location of thermal features

2.4 Hydrothermal Alteration

Secondary minerals in the area occur as replacement of the leached original minerals and as precipitate around thermal springs. There are two areas where replacement exists, in Kematu Mineralised Zone and around Lake Maughan.

The assemblage of secondary minerals in Kematu consists of illite, illite-smectite, quartz, calcite, biotite and laumontite. The above assemblage possibly reflects two episodes of alteration by neutral-pH type fluids. The first one may have a fluid temperature of greater than 300^{o} (biotite and quartz) and the other one may be about $180\text{-}220^{o}C$ (illite). Both mineral assemblages represent fossil hydrothermal systems which are associated with vein-type mineralisation of gold, copper and iron-copper sulfides.

Extensive alteration commonly found in the crater regions of Philipine Quaternary volcanoes (e.g. Alto Peak, Leyte) did not develop in Mt. Parker. Altered rocks around Lake Maughan occur in small patches along the structures. The assemblage consists of alunite, quartz, opal and diaspore suggesting the presence of an acid condensate zone beneath Mt. Parker.

On the other hand, mineral precipitates occur on the rims of thermal springs around Parker Volcano. In the chloride springs at the eastern flanks of Mt. Parker, spring deposits include aragonite, calcite, and halite. Halite evolve from evaporation of chloride-saturated fluids, while travertine deposits reflect oversaturation of waters with respect to calcium carbonates.

3.0 GEOCHEMISTRY

Impressive array of thermal features manifest on the eastern and northern regions of Mt. Parker prospect. Northeast and northwest-trending faults control the distribution of such features around the volcano. These faults and associated features are:

- o Salmotan Fault with Estaw and Kule springs;
- o Parker Fault with Maughan springs;
- o Basag Fault with Tinulang, Bagong Silang and Islakit springs;
- o Bungo Fault with Bungo springs.

The structures chanelling the thermal waters to Salvan springs lie concealed beneath the thick pile of pyroclastic deposits.

3.1 Classification of Waters

Table 1 presents the composition of the water samples from the springs. Most of the samples have good ion balance indicating good analytical methods. The ternary system of the relative abundance of chloride, sulphate and bicarbonate in the waters permits an "eyeball" assesment of the classification of waters from the thermal springs in Parker (Fig. 3).

Tinulang, Islakit, Bagong Silang, Salvan and Bungo, all effusing within an 11-km radius east of Mt. Parker fall on the chloride corner of the ternary plot. Sodium chloride precipitates on the rim of these spring affirm the chloride saturation in the waters of the springs.

Waters from the springs in the crater region of Parker Volcano plotted on the sulphate corner of the diagram. Water sample from Lake Maughan likewise plotted in sulphate corner but is more shifted towards the bicarbonate side. The composition of waters from the crater region indicates an underlying steam-heated water. This type of water evolved from ascending hot sulfide-rich gases from the reservoir which were admixed with the cold meteoric waters near the surface.

Kule contains high proportion of sulphate. In contrast with the Maughan springs, acid-condensate is not likely the medium that caused sulphate enrichment in this spring. It could be more related to the passage of chloride waters in sulfur-bearing sedimentary strata.

The bicarbonate comer of the ternary plot defines the composition of the waters of Cotabato Basin. Estaw water samples plot on the bicarbonate comer signifying a meteoric origin for these waters. Estaw will be used, henceforth, as the ground water end member of the waters in Mt. Parker.

3.2 Sources of Fluids

The sources of fluids emanating from the thermal features is analysed from the point of view of the conservative elements in primary waters.

The ternary plot of the hydrophile constituents in mature waters (Fig. 4) shows depletion of lithium in all the samples, suggesting that the waters did not evolve from a simple rock leaching. Most of the water samples clustered between B/Cl ratio of 0.015 to 0.023. This region of

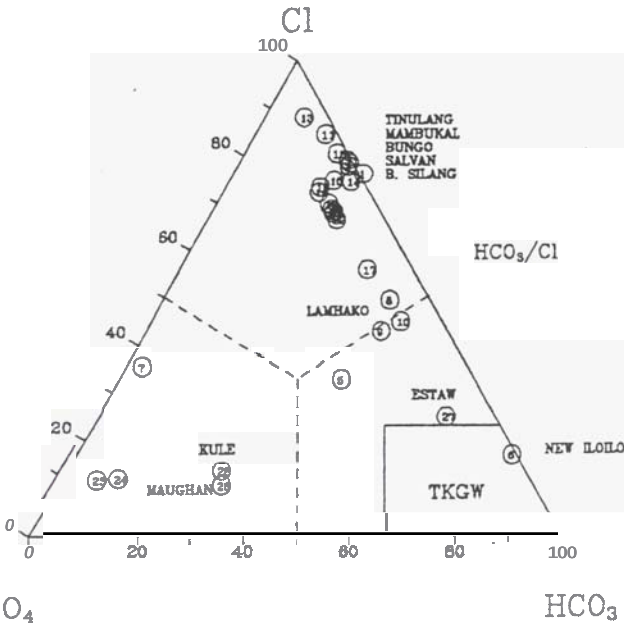

Fig. 3 Cl-SO_4-HCO_3 Ternary Diagram

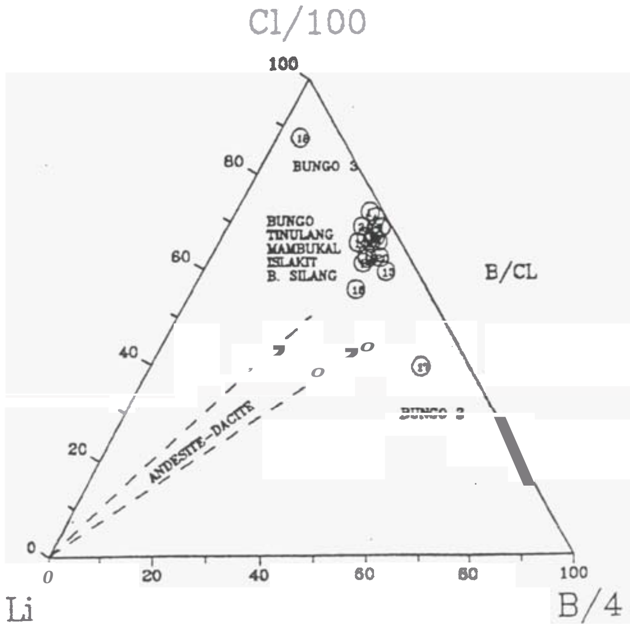

Fig. 4 Cl-B-Li Ternary Diagram

	Name	CATIONS Na	K	Ca	Mg	Fe	Rb	Li	ANIONS Cl	HC03	C03	S04	B	SiO2
	MAMBUKAL 1	2210	79.2	266	102.0	0.12	0.07	1.33	3550	1192	0.0	81	49.90	76
	MAMBUKAL 2	2450	83.6	341	118.0	0.16	0.00	1.42	4160	1130	0.0	69	70.80	75
	MAMBUKAL 3	2720	90.1	381	132.0	0.07	0.07	1.52	4715	1210	0.0	50	79.60	76
	MAMBUKAL 4	3280	113	326	143.0	0.07	0.09	1.77	5570	1503	0.0	45	84.90	78
	N ILO 1	297	30.3	10	3.2	0.04	0.04		178	232	6.7	140	12 1	75
	N LO 2	250	26.6	10	2.9	0.15	0.05		112	544	29.0	6	2.60	72
	SIMAN PULA	170	0.0	27	0.7	0.19		0.0 1	120	10	0.0	10	0.9 5	31
	SIMAN SUFU	960	25.6	26	31.1	0.05	0.04	0.70	1040	1252	0.0	1252	18.30	56
	SIMAN BONG	1025	27.5	143	32.6		0.04	0.74	1140	1195	0.0	337	20.80	60
	SIMAN LAW	1020	27.5	143	31.1	0.23	0.04	0.70	1120	1188	10.6	196	18.90	57
	TINULANG 1	1028	97.3	74	32.6	1.14	0.39	2.13	1720	270	11.1	47	27.80	160
	TINULANG 2	954	90.1	71	10.9	0.30	0.37	1.96	1570	341	0.0	44	29.30	156
	ISLAKIT	892	58.3	77	5.4	0.20	0.22	1.52	1496	127	4.8	77	34.90	138
	B. SILANG	322	29.7	9	1.0	0.66	0.08	0.74	480	150	0.0	16	9.34	118
	SALVAN	41	34.8	45	9.1	0.43	0.10	0.89	680	180	0.0	52	13.00	161
	BUNGO 1	954	76.8	76	14.9	0.62	0.32	3.70	1507	380	[illegible]	204	33.30	170
	BUNGO 2	849	62.5	77	17.7	2.27	0.23	3.05	1269	8 14	4.0	198	66.30	IE0
	BUNGO 3	763	50.8	86	18.0	0.42	0.18	1.00	1200	293	E.7	I47	2.5 1	142
	BUNGO 4	694	43.2	82	15.7	0.46	0.14	0.97	1071	328	2.9	140	17.50	135
	BUNGO 5	632	39.5	85	22.5	0.42	0.13	0.92	1003	327	3.d	134	20.60	132
	BUNGO 6	543	23.6	69	19.0	1.09	0.07	0.68	819	276	2.9	108	12.10	117
	BUNGO 7	557	28.7	71	24.2	0.0 1	0.1 1	0.76	822	304	0.0	112	14.40	117
	BUNGO 8	568	26.5	66	22.7	0.12	0.09	0.74	832	205	2.9	114	14.00	120
	MAUGHAN 1	301	23.5	338	61.6	8.6 1	0.04	0.1 2	150	206	0.0	1434	8.74	90
25	MAUGHAN 2	306	23.7	328	60.0	11.33	0.04	0.10	150	135	0.0	1502	7.87	a7
26	L. MAUGHAN	130	12.3	148	43.5	1.05	0.03	0.10	78	234	7.2	447	1.47	47
27	ESTAW	125	5.8	20	3.1	0.95	0.06		84	221	3.4	31	1.21	41
28	KULE	689	11.9	7	4.3	0.49	0.0 1	0.1 1	216	474	6.2	925	6.05	102
29	BANGA RIVER	15	4.8	26	8.6	0.02					0.0		1.25	82

Table 1: Chemical constituents of thermal waters

the diagram almost coincides with the systems hosted by dacitic to andesitic rocks (B/Cl = 0.06-0.03), with slight shift towards the chloride comer. The obvious homogeneity of the B/Cl ratios indicates a single source for thermal waters.

33 Geothermometry

The ternary plot of K-Na-Mg contents of waters appear on Fig. 6. The diagram indicates that the waters come from a reservoir of 200-240°C and reequilibrated between 100-130°C as the fluids migrate towards the surface. The sample from Islakit represents partially equilibrated waters giving an estimated reservoir fluid temperature of 200°C.

Na-K-Ca is employed to compensate for the interference of calcium in the reaction of potasium and sodium in the reservoir. This gave an estimated reservoir fluid temperature gave about 123-193°C, which is 20-30°C less than that of K/Na geothermometer.

3.4 Mixing Models

The applicability of the warm spring (silica) mixing models (Fournier,1981) is based on the assumptions that: (1) no silica deposition occured before or after mixing; (2) quartz is the controlling silica phase of the high themperature component ofthe mixed waters; and (3) no conductive cooling occured after mixing.

The warm spring mixing diagram shows three dilution trends for silica. The first is the dilution line defined by the Tinulang and Islakit. Physically, these springs both percolate along Basag Fault, and therefore undergo the same dilution trends. The dilution line predicts a reservoir fluid temperature of about 158°C.

The second dilution line is defined by the Bungo and Bagong Silang samples with predicted reservoir temperature of about 180°C. The third dilution line is defined by the extension of Salvan to the boiling temperature. The line shows high dilution for Salvan springs with an estimated reservoir fluid temperature of about 228°C.

The hot spring mixing model described by Fournier and Truesdell (1976) makes use of a chloride-enthalpy plot (Fig. 9) and works best where the initial temperature of the hot water component is above 200°C. The chloride concentration of the springs are plotted against the enthalphy of the springs. A dilution line is drawn from the groundwater endmember, passing through the clusters of data up to the ideal steam line. The intersection is assumed to be the characteristic of the parent aquifer which produced the fluids emanating from the spring. The diagram gives a reservoir temperature of about 230°C, with salinity of about 5,000-5,200 ppm Cl.

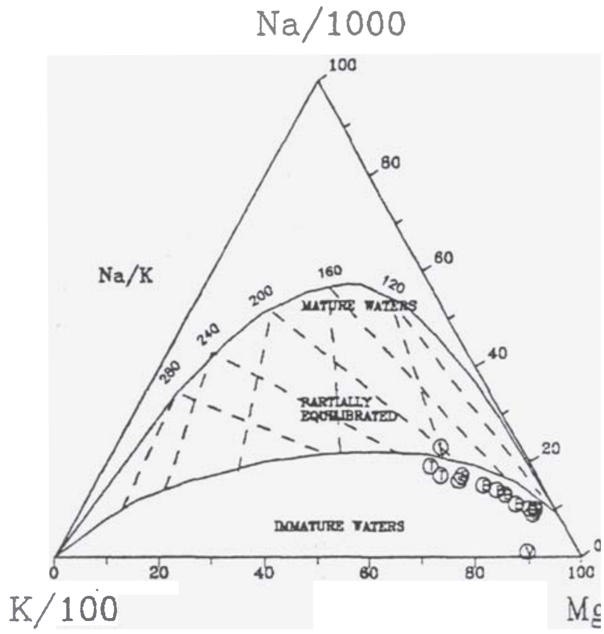

Fig. 5: K-Na-Mg Ternary Diagram

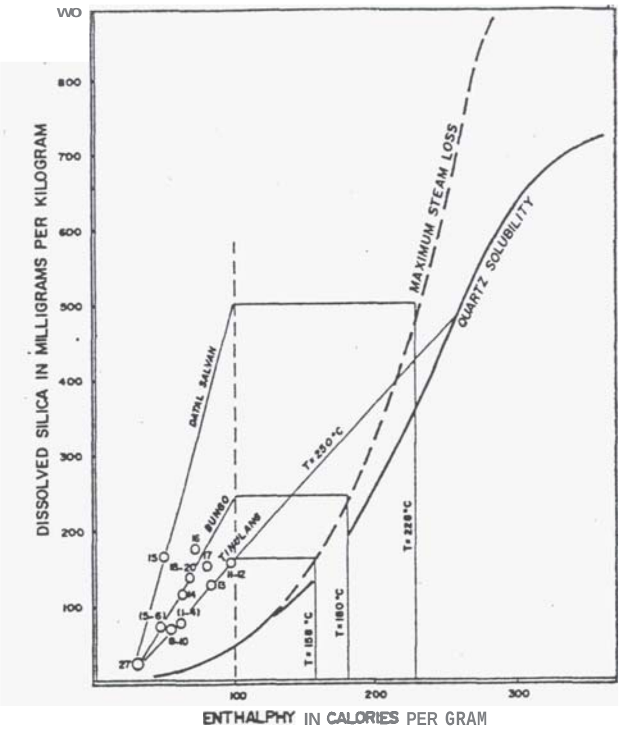

Fig. 6: Warm spring mixing model

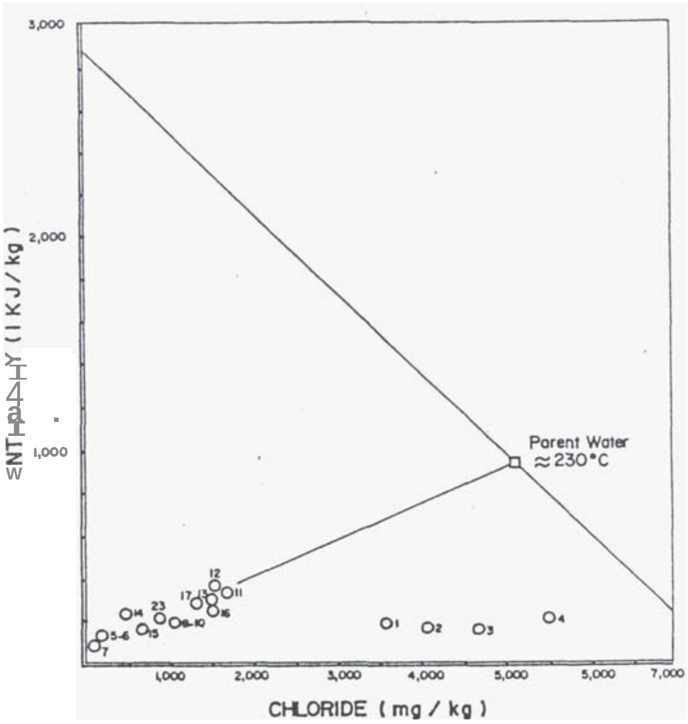

Fig 7: Hot spring mixing model

4.0 HYDROTHERMAL MODEL

The rainfall data in Cotabato Basin showed that the Daguma Range and Mt. Parker receive the largest amount of precipitation in the area. It also showed that precipitation and surface runoff contribute much of the input in the water budget of the basin (LWUA, 1990). Water recharge, therefore, possibly comes from the Daguma Range in the west, and partly from the crater region of Mt. Parker.

The invading water recharges encounter hot rocks beneath Mt. Parker. The waters mix with hot volatiles escaping from the hot rocks resulting to the fluid enrichment of chloride, sodium, potasium and other chemical constituents. The waters are likewise heated up, and subsequently start to billow upward towards the crater region of Parker Volcano. Thermal waters pass through Parker, Asamblak and Bululfet Faults.

Volatile components are liberated from the single-phase reservoir fluids as the pressure and temperature decline towards the surface. Gases, such as hydrogen sulfide and carbon dioxide mix with the cold water countefflow coming from the crater. The gases are subsequently oxidised, resulting in an acid-condensate zone beneath Mt. Parker crater.

The crater lake acts as the catchment of the ascending gases as reflected by the high sulphate level of the lake. Lake waters also dilute the acidic water coming from the acid condensate zone – the reason for the high pH in the Maughan hot spring samples despite dominance of sulphate. The lake may also have quenching effects on the heated-waters, thus retarded the development of extensive altered grounds on the surface.

The chloride brines bereft of hydrogen sulfide and hydrogen in the

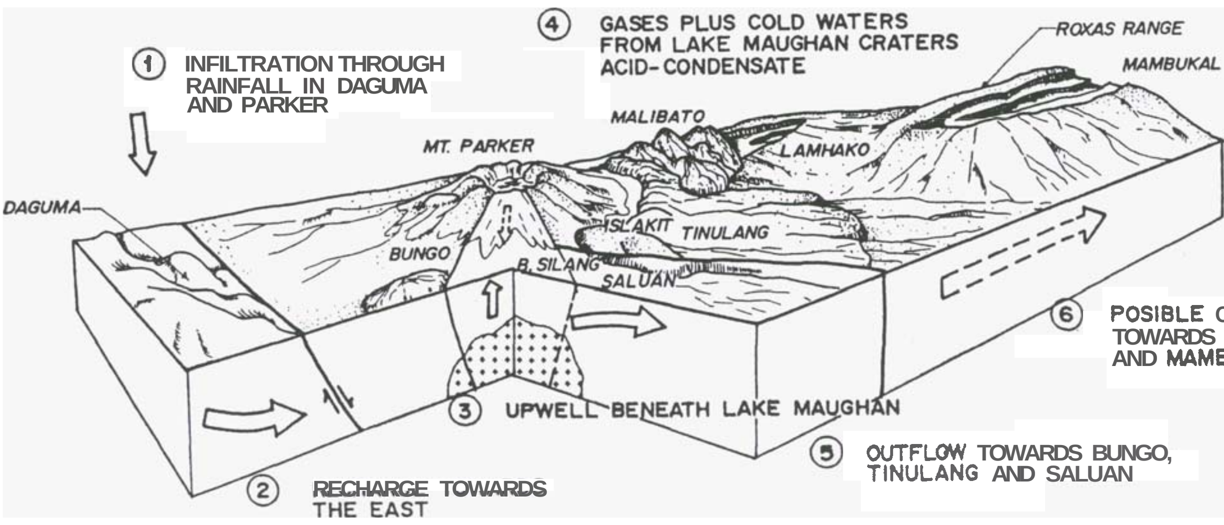

Fig 8 Hydrothermal model of Mt. Parker geothermal system

reservoir migrate laterally towards the south, east, and northeast. During the migration process, the hot brines possibly encounter carbonate horizons in the reservoir, thereby saturating their composition with calcium and bicarbonate. Waters percolate through: (1) Bungo Fault and effuse in Bungo springs; (2) Basag Fault into Bagong Silang, Islakit and Tinulang (3) probably Salvan Fault to Salvan; and (4) Salmotan Fault to Kule and Estaw. Dilution by shallow meteoric waters modified the composition of the brines. The most diluted springs are Kule and Estaw, both lying farthest from Mt. Parker.

5.0 ACKNOWLEDGEMENTS

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