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GEOCHEMICAL ASSESSMENT OF LOW-TEMPERATURE GEOTHERMAL FIELDS IN PHILIPPINE GEOTHERMAL SYSTEM: THE CASE OF MABINI (BATANGAS) AND MONTELAGO (NAUJAN, ORIENTAL MINDORO) GEOTHERMAL PROSPECTS

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ABSTRACT

The geothermal potential of Mabini and Montelago prospects is evaluated by the employment of geochemical tools: the Cl-SO_4-HCO_3 and Cl/B vs Cl plots, and the fluid-mineral equilibrium diagrams and geothermometry. The former set is to select the spring(s) fit for geothermometry calculations by identifying the types of waters and hydrological processes, while the latter set is to evaluate the state of equilibrium of the aquifer of the selected spring.

In Mabini prospect, the springs fit for geothermometry calculations originated from seawaters that percolated at depth and reacted with the rock. These springs attained fluid-mineral equilibria at depth. The temperature of the aquifer feeding this type of springs ranges from 150 (Tquartz) to 200°C (NaKCa at β=1/3).

In Montelago prospect, its springs originated from lake waters that percolated at depth and reacted with the rock. These springs also attained fluid-mineral equilibria. The aquifer temperature range from 150 (TChalcedony) to 190°C (Na/K-Fournier).

1. INTRODUCTION

It is always been the primary objective in geochemical exploration to give the *best* temperature estimates of the aquifers feeding the springs. However, during the course of the evaluation, a more important question arises that bears a greater practical use: *which spring(s) and/or gas manifestation(s) are suited for geothermometry.*

For a spring to be a candidate for geothermometry estimates, usually, it is with the largest flow rate, highest sampling temperature and Cl are pre-requisites for temperature calculations (Ellis and Mahon, 1977). Another method is to calculate every geothermometers of each manifestation and find congruence through a series of temperature cross-plots (e.g. Giggenbach , 1991; Reed, 1991). The former method, although it is more direct, the variable measurements, such as flow rate and temperature, of a spring render this method less dependable. The latter seems logical, however, it requires a more in-depth knowledge about the hydrology in the area than routine calculations.

A more logical approach is to identify the hydrological processes affecting the chemistry of each spring. This includes the effects of surrounding non-thermal waters (surface/groundwaters, and seawater) and the rock on the chemistry of thermal waters. In this way, springs can be evaluated and selected based from the natural processes.

In this contribution, a method employing the tools of Giggenbach (1991) and Arnorsson et al., (1995) is used and applied to natural waters of Mabini and Montelago prospects of Philippines geothermal systems. Its objectives are to identify the processes and discriminate the most likely thermal waters that will give the best temperature of the deep aquifers feeding the springs.

Mabini and Montelago prospects (Fig. 1) are classified as low-temperature geothermal resources, with subsurface temperature estimates of 150 to 200°C. Extensive geological and geophysical evaluation of the prospects are presented elsewhere (PNOC-EDC, 1989a and b). At present, no well deep drilling was conducted to confirm these temperature estimates.

1.1 The Mabini (Batangas) Geothermal Prospect

The Mabini Prospect (Fig. 1a) is located in the Calumpan Peninsula, about 100 kms south of Manila, and 15 kms southwest of Batangas City. The area is covered mostly by Pliocene to Pleistocene volcanic effusive and reworked materials. Few Upper Miocene to Recent sedimentary deposits are also exposed. No large intrusive or metamorphic bodies exist within the general vicinity of the Calumpan Peninsula .

The hydrothermal manifestations in Mabini are dominated by thermal springs and cold altered ground. The thermal springs in the area have generally low flow rates (<1 l/s) with temperature range of 30 to 90°C. These springs are usually marked by travertine and limonite deposits. There are two group of springs in the Mabini prospect. The first group of springs is located at the Calumpan Peninsula, while the second group is found at Maricaban Island .

The Calumpan springs are the Mainit, San Teodoro, and Sto. Tomas, Pulang Lupa, Hulo, and Solo springs. Except for Pulang Lupa and Sto. Tomas springs, the rest of the springs are very near the shore (less than 5 meters from the shoreline), along the tide lines. Pulang Lupa and Sto. Tomas are located 100 masl, and about 2 kms from the nearest shore.

The Maricaban group of springs is the Papaya and the Gamao springs. These springs are found along the shorelines. Papaya hot springs are a cluster of springs along the tide lines, while the Gamao spring is enclosed in the circular concrete pool, emplaced in the coralline limestone.

It must be emphasized that no fumarolic or solfataric activities are found in the Mabini prospect. Gas chemistry data presented from previous study (PNOC-EDC, 1989a) are from the boiling springs of Mainit. These gas data are expected to be significantly contaminated by gases from the atmosphere, caused by mixing with air-saturated groundwater. The use of these data were found to be of little value in predicting deep temperatures (PNOC-EDC, 1989a). In this paper, temperatures are estimated using solute geothermometry.

1.1 Montelago (Naujan, Oriental Mindoro) Geothermal Prospect

The Montelago prospect (Fig. 1b) is about 170 kms south of Manila, and 30 kms southeast of Calapan, the provincial capital of Oriental Mindoro). The area lies along the northwest-trending belt of late Pliocene-Quaternary volcanoes that form a narrow strip of low-lying mountains between the sea to the north and Lake Naujan to the southwest. Seismic and aeromagnetic surveys indicate that the volcanic pile is underlain by about 2500-m think of tertiary sediments, which in turn, rest upon a magnetic basement. The latter is believed to represent Mesozoic ultramafic rocks (PNOC-EDC, 1989b).

The hydrothermal manifestations in Montelago are dominated by active thermal springs and cold altered ground. The thermal springs in the area have generally low (<1 l/s) to moderate flow rates and usually have travertine and limonite sinter deposits.

There are two major group of springs found in the prospect. The first group of springs (Buloc-buloc and Lugta) is located on the seashore along the tide lines, while the second group (the Montelago springs) is along the shoreline of Lake Naujan. Some thermal waters (not shown in the map), with temperatures slightly above 30°C are found at the town of Naujan (Naujan Poblacion springs) and some springs south of Mt. Montelago (Patao, Maluanluan Pola springs).

Like the Mabini prospect, no fumarolic or solfataric activities are found in the Montelago prospect. Gas chemistry data presented from previous study (PNOC-EDC, 1989b) are from the boiling springs of Montelago. In this paper, temperatures are estimated using solute geothermometry.

2. GEOCHEMICAL EVALUATION OF THERMAL WATERS FOUND IN THE PROSPECTS

2.1 Cl-SO_4-HCO_3 diagram

The Cl-SO_4-HCO_3 diagram is devised by Giggenbach (1991) to identify the types of waters in the prospect. Its objectives are:

1) to identify the type of waters in the area, and
2) to weed out unsuitable waters for geothermometry calculations.

In Fig. 2, the types of waters in Mabini prospect are:

The peripheral waters: These are the waters that lie close to the HCO_3 apex. These waters are usually thermal waters that are heavily contaminated by river water or surface or groundwater in the area. These waters are represented by unlabeled circle.

The steam-heated waters: These are neutral pH waters that lie along the SO_4-HCO_3 axis. The enrichment of SO_4 and HCO_3 are caused by mixing and oxidation of upflowing steam (which consists of steam, CO_2 and H_2S gases) and groundwater. They are represented by circles labeled as Solo (SO), San Tomas (ST), and Pulang Lupa (PL) springs.

The mature waters: These are neutral pH waters that lie close to the Cl apex, and along the Cl-HCO_3 axis. These waters are least affected by mixing of ground or surface waters. Samples of this water are best suited for geothermometry calculations. These are the Papaya (PP), Mainit (MA), Gamao (GM), and San Teodoro (TD) thermal waters.

In Figure 3, the Montelago prospect has only two types of waters. These are:

The peripheral waters: These include the Maluanluan Pola (ML), Buloc-buloc (BB), and Patao (PA) thermal waters. The lake waters are also plotted as peripheral waters.

The mature waters: These are the Montelago (MT) and Lugta (LG) thermal waters. These are the only waters best suited for geothermometry calculations.

Sea and lake water mixing with the meteoric waters could also be considered using this type of figure. In Mabini, a line could be drawn from the HCO_3 apex to the composition of seawater. This mixing line will intersect most of the mature waters (San Teodoro and Gamao).

Similarly, for Montelago waters, a line from the HCO_3 apex to sea and lake water intersects most of the peripheral waters (Maluanluan Pola, Patao, and Naujan) and mature waters (Montelago and Lugta).

Although the Cl-SO_4-HCO_3 plot can evaluate boiling and mixing to select "mature" waters for geothermometry calculations, it falls short in discriminating the effect of rock dissolution. The use of Cl/B and Cl plots can able to discriminate this type of process as described below.

2.2 Cl and B in the Prospects

Cl and B are chemically inert, non-reactive constituents and usually used as tracers. Arnorsson et al., (1995) recently proposed a model to explain the origin and chemistry of Cl and B in the cold and thermal waters located along the shore in the southern lowland of Iceland. In their model, they assumed seawater and rock to constitute the only sources of these elements. The distribution of Cl and B in these type of natural waters are explained by:

a) the atmosphere, i.e., seawater spray and aerosols
b) the rock being dissolved by the water, and,
c) seawater

Cl and B concentrations in rainwater, surface waters, and non-thermal groundwaters are considerably lower than thermal water. B ranges from less than 0.01 to a few mg/kg, but Cl from less than 1.0 to several tens of mg/kg. The Cl/B mass ratio in natural waters ranges from as little as 1 to that of seawater at 4350 (Arnorsson et al.,1995). A number of studies have been conducted to determine the abundance of Cl and B in andesitic rock as compiled by Harder (1969) and Fuge (1974). The average Cl/B mass ratio of andesitic rock is 10 with Cl of 200 mg/kg.

<u>Cl and B of Mabini waters</u>

Fig. 4 shows the distribution of Cl and B of natural waters in Mabini prospect with respect to different origins as traced through their Cl/B ratios. The surface waters (represented by open circles) possess Cl/B mass ratio in the range of 30 to 100 with Cl less than 25 mg/kg. Their B contents range from 0.1 to 1.0 mg/kg.

Their Cl values are typical for surface and non-thermal waters in any parts of the world, with Cl being largely derived from seawater spray and aerosols. However, the lower Cl/B ratios of these waters, relative to seawater (mass ratio of local seawater samples = 3870), indicate that they have reacted with the rock. Boron's primary source come the rock as must be some of the Cl.

Local seawater is delineated at Cl/B of 3870 and Cl of 19,000 mg/kg. Mixing of seawater with surface waters is represented by a mixing line that runs through Solo (SO) spring and Mainit(MA) artesian well.

Aside from surface mixing of meteoric and seawater, there are a number of springs that seems to have mixed at depth and reacted with the rock. These are thermal waters that may have geothermometry significance, and classified as:

- Type 1: seawaters that percolated at depth and reacted with the rock (springs with seawater salinity but lower Cl/B mass ratio)
- Type 2: thermal waters originated from the mixture of meteoric and Type 1 waters (springs with Cl higher than meteoric waters but lower than seawater; they have Cl/B ratio similar to Type 1 fluids)

Type 1 fluids are the Mainit (MA), Gamao (GM) and Papaya (PP) springs. Their measured temperatures range from 60 to 95°C. These thermal waters possess Cl/B mass ratio in the range of 100 to 1,000 with almost seawater salinity, 19,000 mg/kg, but higher B contents ranging from 20 to 150 mg/kg.

The seawater Cl level of these springs indicates that most of their Cl was derived from the sea, however, their low Cl/B ratios, indicate that they have significantly reacted with the rock, rendering B enrichment in their chemistry. These fluids were seawater that may have percolated deep in to the formation, leached B from the rock, and gained heat in the process.

Type 2 are thermal waters that were may be considered a mixture of the Type 1 and meteoric waters. This water can be represented by Mainit – 4 (MA4).

This spring has Cl/B of 260 Cl of 5,840 mg/kg. Its Cl/B ratios indicate significant reaction with the rock, and their Cl indicates minimum seawater contamination. These springs may render dependable values for geothermometry values.

<u>Cl and B of Montelago waters</u>

Figure 5 shows the distribution of Cl and B of natural waters in Montelago prospect. The surface waters are represented by Patao (PA) springs. They possess Cl/B mass ratio of 50 with Cl less than 30 mg/kg. Their B contents are less than 1.0 mg/kg. The Cl/B ratio of lake waters is 9,000.

Mixing of seawater and Lake Naujan with surface waters are represented by mixing lines. These mixtures are Maluanluan Pola (ML) and Naujan Poblacion (NU) springs.

Similar to Mabini waters, there are two types waters that may have geothermometry significance:

- Type 1: lake waters that percolated at depth and reacted with the rock (springs with Cl similar to lake waters but lower Cl/B mass ratio)
- Type 2: thermal waters originated from the mixture of meteoric and Type 1 fluids (springs with Cl higher than meteoric waters but lower than the lakewaters; their Cl/B ratio is similar to Type 1 fluids)

Type 1 fluids are the Montelago (MT) springs. These waters have Cl level (3,100 mg/kg) slightly lower than the lake waters (3,900 mg/kg). They have lower Cl/B ratio (40) than lake waters indicating B leaching from the rock. It is likely that these springs are dominantly lake waters that percolated down the formation. Their Cl values indicate slight mixing with meteoric waters as it percolated along the aquifers, before re-emerging as springs.

Type 2 fluids are the Lugta (LG) springs. These waters represent mixture of Type 1 and meteoric waters. These waters have Cl/B of 40, similar with Montelago springs, but with Cl of 850 to 950 mg/kg. Their similar Cl/B ratios but lower Cl indicate mixing with meteoric waters and a Type 1 fluids.

2.3 Discussion of Results

The employment of Cl-SO_4-HCO_3 and Cl/B vs Cl plots enables us to delineate the types of fluids and the processes in the prospects. The former gives the general types of fluids, while the latter identify the origin and processes affecting the chemical make-up of the fluids. Below is the list of the selected springs from each prospect:

In Mabini prospect : Mainit, San Teodoro, Gamao
In Montelago prospect: Montelago and Lugta

However, the previous plots do not indicate the state of fluid-mineral equilibria of each spring. The deep origin of these waters does not guarantee that these waters are fit for geothermometry calculations.

The following discussion focuses on an evaluation of the state of equilibria using fluid-mineral equilibria diagrams (Reed, 1991) of selected Type 1 and 2 springs in the prospects. In Mabini, these are represented by Mainit (MA) and Mainit-4 (MA4) springs, while in Montelago, these are the Montelago (MT) and Lugta (LG) springs., respectively . Its objective is to evaluate the waters that had attained close equilibrium at depth, thereby resulting in greater confidence in using its geothermometry estimates.

3. GEOTHERMOMETRY CALCULATIONS

The fluid-mineral equilibria diagrams are presented in Figures 6 to 9, while the list of computed temperatures of each selected spring is shown in Table 1.

3.2 Fluid-mineral equilibrium diagram

<u>Mabini Prospect</u>

In Mabini, for Mainit, a Type 1 fluid, there are more fluid-equilibrium lines converging at 125°C, than Mainit-4 . For Mainit-4, a Type 2 fluid, it seems that there is limited convergence of equilibrium lines. It is likely that the former attained a closer fluid-mineral equilibrium at depth than the latter.

In this case, there is greater confidence in using the computed temperatures based from Mainit spring data than other springs in Mabini prospect. The computed temperatures in Table 1 of the aquifer feeding this spring may range from 150 (Tquartz) to 200°C (NaKCa at β=1/3).

Montelago Prospect

In Montelago, the Lugta spring, a Type 2 fluid, has more lines converging at 195°C, than the Montelago spring. It is likely that the former attained closer fluid-mineral equilibrium at depth than the latter.

In this case, there is greater confidence in using the computed temperatures based from Lugta spring data than other springs in Montelago prospect. The computed temperatures of the aquifer feeding this spring may range from 150 (Chalcedony) to 190°C (Na/K-Fournier).

3.2 Discussion of results

The tools described above enable us to select the most appropriate spring data for solute geothermometry based from the natural processes affecting their chemistry and the state of fluid-mineral equilibria. We can also compare the temperature estimates using the Na-K-Mg ternary plot of Giggenbach (1988) as presented in Figures 10 and 11 for Mabini and Montelago prospects, respectively.

In Fig. 10 the temperature ranges (Na/K) from 160 to 180°C, while Fig. 11 gives a temperature of 200°C. Both these plots give similar estimates as from the previous section. The partial maturity of these waters also compliment the results using fluid-mineral equilibrium plots of Reed (1991).

4. SUMMARY AND CONCLUSIONS

This contribution presented a re-evaluation of the usual tools in geochemical exploration. These tools are the Cl-SO_4-HCO_3 and Cl/B vs Cl plots for identifying the types of fluids and the processes, and fluid-mineral equilibrium diagrams and geothermometry for temperature estimates. The former set is to select the most appropriate spring for temperature estimates, while the latter set is to evaluate the state of equilibrium of the aquifer of the selected spring for geothermometry calculations.

Below are the following important findings deduced from this study:

In Mabini prospect

1. The springs fit for geothermometry calculations originated from seawaters that percolated at depth and reacted with the rock. These springs attained fluid-mineral equilibrium.

2. The temperature of the aquifer feeding this type of spring has temperature range of 150 (Tquartz) to 200°C (NaKCa at β=1/3).

In Montelago prospect

1. The springs fit for geothermometry calculations originate from lake waters that percolated at depth and reacted with the rock. These springs also attained fluid-mineral equilibrium.

2. The temperature of the aquifer feeding this type of spring has temperature range of 150 (Chalcedony) to 190°C (Na/K-Fournier).

These temperature estimates are similar to results obtained using the Na-K-Mg ternary plot of Giggenbach (1991).

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Table 1: Computed temperatures in °C of selected springs

Spring	Mainit	Mainit-4	Montelago	Lugta
Prospect	Mabini	Mabini	Montelago	Montelago
Type	Type 1	Type 2	Type 1	Type 2
Sampling temp.	863	41	96	59
Quartz	149	112	106	170
Chalcedony	123	82	76	147
Na/K(1)	196	194	194	185
K-Mg (2)	156	95	135	98
Na-K-Ca (3)	280	188	241	164
Na-K-Ca (4)	207	186	198	175

Notes:
Type1: Sea/lake waters that percolated down the formation
Type 2: Mixture of Type 1 and meteoric waters
(1) Fournier, 1991 (4) Fournier, 1991at $\beta = 1/3$
(2) Giggenbach, 1991
(3) Fournier, 1991 at $\beta = 4/3$

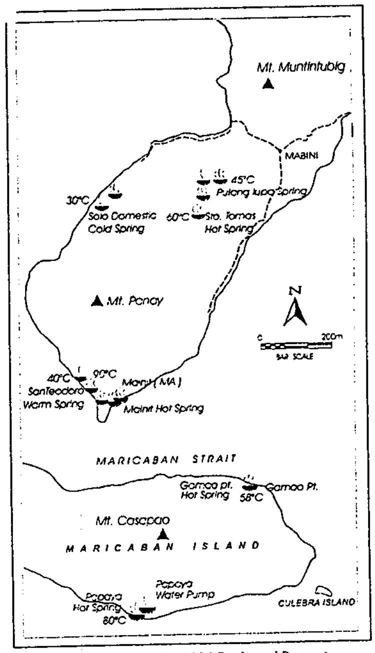


Figure 1a: Map of springs in Mabini Geothermal Prospect

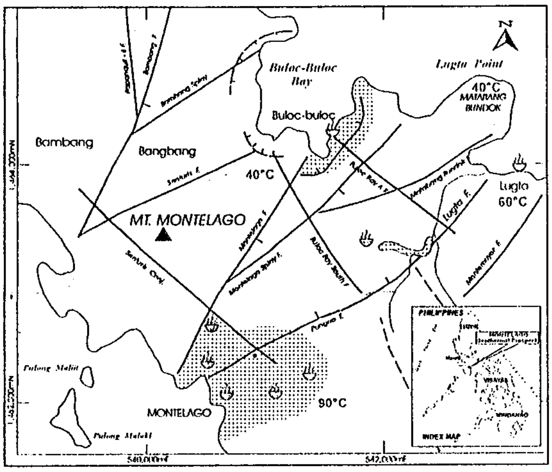


Figure 1b: Map of Springs of Montelago Geothermal prospect

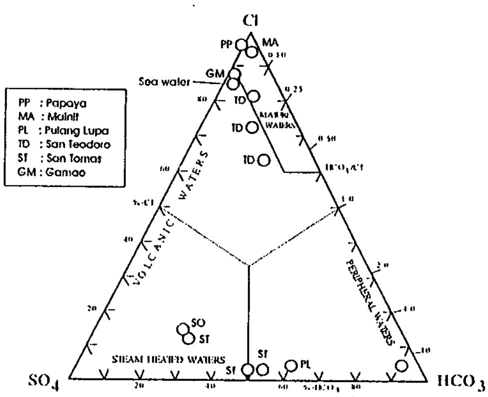


Figure 2: $Cl-SO_4-HCO_3$ Plot of Mabini thermal waters

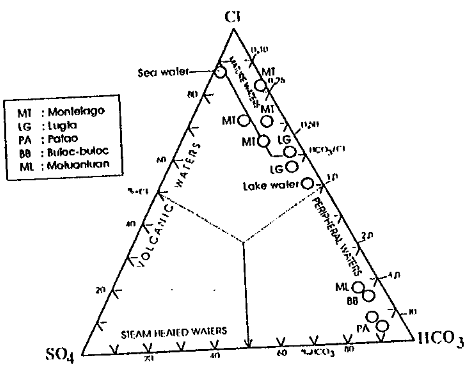


Figure 3: $Cl-SO_4-HCO_3$ Plot of Montelego Prospect

Figure 4: Cl/B vd Cl plot of Mabini waters

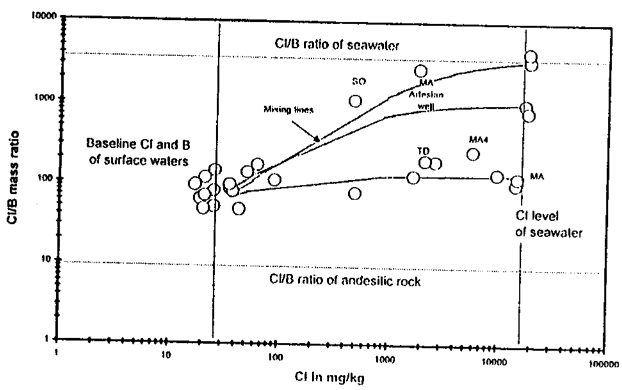


Figure 5: Cl/B vs Cl plot of Montelago waters

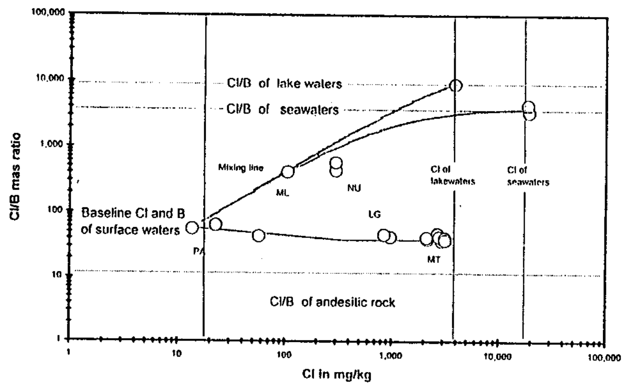


Figure 6: Fluid-mineral plot of Mainit spring (Type 1 fluid)

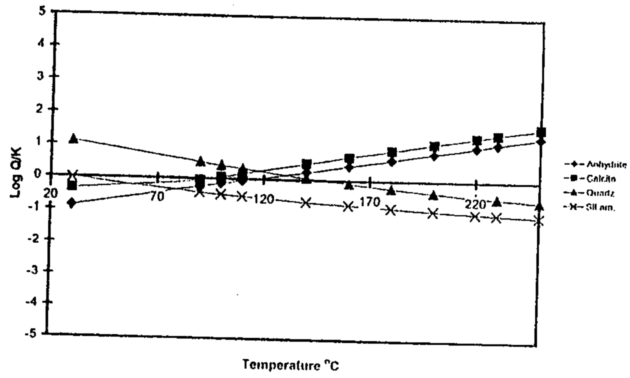


Figure 7: Fluid-mineral plot of Mainit-4 spring (Type 2 fluid)

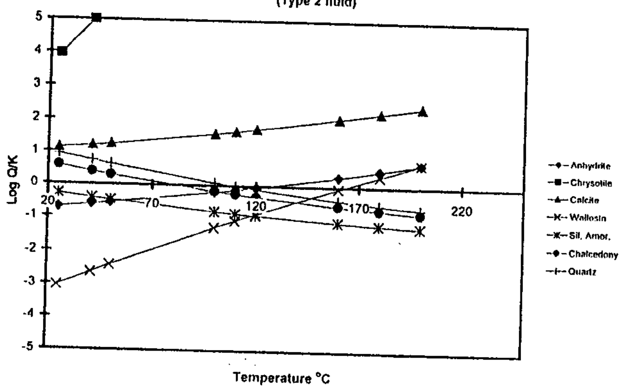


Figure 8: Fluid-mineral diagram of Montelago spring (Type 1 fluid)

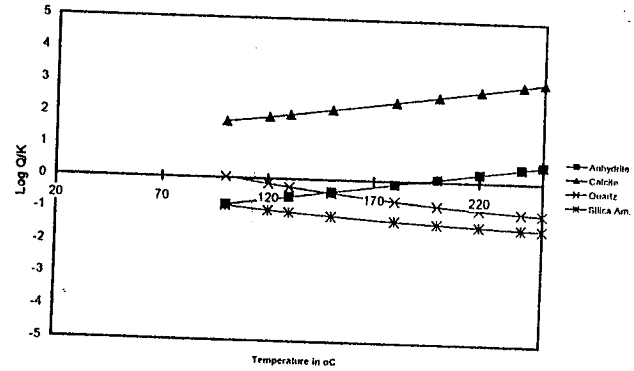
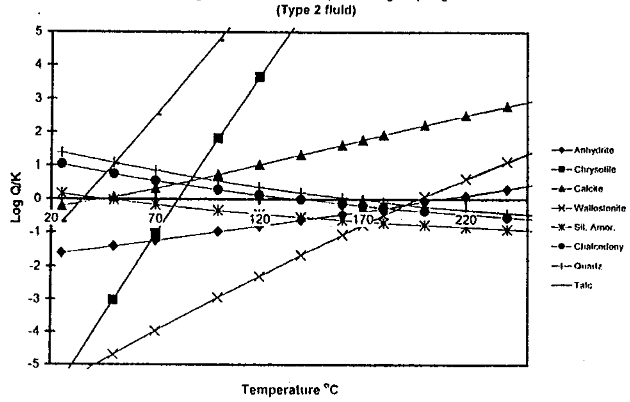


Figure 9: Fluid-mineral plot of Lugta spring (Type 2 fluid)



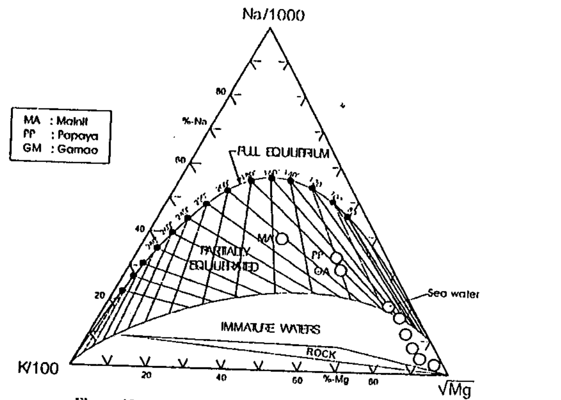


Figure 10 : Na-K-Mg ternary plot of Mabini prospect

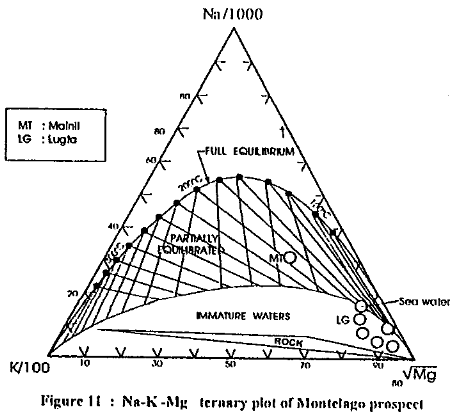


Figure 11 : Na-K-Mg ternary plot of Montelago prospect