HYDROCHEMISTRY AND GEOTHERMOMETRY OF THE BAN PONG KUM, BAN SOP PONG AND BAN PA PAE GEOTHERMAL FIELDS, N-THAILAND.

Thanu Srinavavongsa*
UNU Geothermal Training Programme
National Energy Authority (NEA)
Grensasvegur 9, 108 Reykjavik
ICELAND

*Permanenet address:
Geochemical Section
Economic Geology Division
Dept. of Mineral Resources
Rama VI Road, Bangkok 10400
THAILAND

ABSTRACT

Most of the active geothermal fields in the world are located on plate boundaries. Although Thailand is not located on any plate boundary, it has extensive geothermal activity on a zone of rather high heat flow and geothermal gradient. Over 60 geothermal fields have been discovered which are scattered from the northern through to the southern part of Thailand. More than half are located in the northern part, like Ban Pong Kum (CM2), Ban Sop Pong (CR6), and Ban Pa Pae (CM4). The chemical data from these areas are studied to evaluate solute-mineral equilibria and for predicting subsurface temperatures using chemical geothermometry. In calculating aqueous species activities quartz equilibrium temperature was selected for reference. On the whole quartz-, CO_2-, H_2S-, CaH-, and HF temperatures are close to the mean temperature but H_2SO_4 temperature is systematically low and NaK temperature and MgK temperature show much scatter. Mineral equilibrium studies indicate that the reservoir fluid is saturated with respect to calcite, and undersaturated with respect to anhydrite and fluorite.

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1 INTRODUCTION

1.1 Scope of work

Utilization of geothermal energy has received increasing attention in Thailand during the last decade. This interest has been followed by exploration and preliminary study of some geothermal fields. Visiting scientists have taken great part in this developing exploration and national scientists have acquired know-how in this discipline.

The United Nations University (UNU) Geothermal Training Programme in Iceland aims to provide practical training and special courses in geothermal resources, including exploration, development and exploitation of geothermal system. The author was awarded an UNU Fellowship to attend this programme which is executed by the Geothermal Divisionof the National Energy Authority (NEA) and operated in cooperation with the University of Iceland. Supervisors and instructors come from these institutions as well as other individual specialized institutes. Each participant receives a practical training in his field of specialization.

Practical training in the chemistry of geothermal fluids provides some basic knowledge of the role of the thermal fluid chemistry in geothermal exploration. This includes water sampling, analysis of the major chemical components and interpretation of the results. Each participant deals with certain problems related to his speciality, sometimes he can bring data from his own country for interpretation. A final report is written at the end of the training programme.

The author brought some chemical data from three geothermal fields in northern Thailand for interpretation in the final report.

2 GEOLOGY AND THERMAL MANIFESTATIONS

2.1 Introduction

Thailand is not located on acrustal plate boundary. Yet, it has extensive geothermal activity on a zone of rather high heat flow and geothermal gradient (Thienprasert et al., 1978). Over 60 geothermal fields have been discovered which are scattered from the northern through to the southern part of Thailand (Fig. 1). More than half are located in the northern part, like Ban Pong Kum (CM2), Ban Sop Pong (CR6), and Ban Pa Pae (CM4) which are the subject of this report.

On a regional scale, hot springs of northern Thailand are related to the margins of a Cenozoic basin. This basin is generally bounded by faults which follow older tectonic patterns that were rejuvenated during Cenozoic times. This is indicated by faults affecting terraces of late Tertiary or Pleistocene age. Some hot springs occur near the margins of Mesozoic or older granite batholiths, or by major fault zones. A Tertiary igneous event has been postulated to explain the Tertiary age obtained by radiometric dating of the crystalline basement complex (Granite) west of Chiangmai basin (Ramingwong et al., 1984).

The CM2 geothermal field lies on an alluvial plain. There are several hot springs distributed over an area about 1 km. The thermal water ascends along faults bordering minor grabens and cutting through sedimentary sequences. Permeability is quite variable depending on the density of fractures in the older complexes. The flow rate is 12.6 l/s and maximum temperature 98°C.

The CR6 geothermal field is located on a small alluvial plain near the slope of a mountain. The hot springs are associated with a fault cutting Triassic granite covered by a thin sequence of Late Carboniferous volcanics. Permeability is provided by the tectonic fractures. The hot springs are distributed over an area of about 100 m^2. The water flow rate is 2.5 l/s and maximum temperature 98°C.

The CM4 field is located in a small valley of the tributaries of Nam Mae Sae. The hot springs are distributed over an area 100 m^2 and are associated with a large fault cutting through a granitic body. The diameter of the two biggest pools are 3 and 4.5 m., respectively. The flow rate is about 22.7 l/s and the temperature is near the boiling point (90-99°C). Algae are abundant in someof the hot springs not directly discharging into the nearby stream. Deposits of silica and other precipitates, together with clay, occur as a coating on boulders bordering the hot pools (Balangue, 1984).

The thermal water of the CR6 and CM4 regions rises up through faults cutting granites or high grade metamorphic rocks. The hydrothermal systems are clearly related to deep circulation within major extensional faults in otherwise impermeable crystalline rocks. The high discharge temperatures and homogeneous composition indicate that mixing with cold meteoric water in the upflow is insignificant which in turn suggests either that the whole hydraulic circuit is restricted to some major faults or that the uprising hot water is insulated by self sealed fractures from shallower and colder aquifers possibly hosted within the crystalline rocks. (UNDP, 1984).

3 SAMPLING AND ANALYTICAL METHODS

3.1 Sampling methods

Water samples from three geothermal fields in northern Thailand, Ban Pong Kum (CM2), Ban Sop Pong (CR6), and Ban Pa Pae (CM4) are interpreted in this report. They were analysed at two laboratories, at the Department of Mineral Resources in Bangkok and the Department of Mineral Resources area 3 in Chiangmai.

The samples were collected into polyethylene bottles. Samples collected for analysing sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe) and manganese (Mn) were acidified by concentrated hydrochloric acid (HCl) to prevent some precipitation of the cations prior to analyses. pH, total dissolved solids (TDS), hydrogen sulphide (H_2S), sulphate (SO_4), fluoride (F), chloride (Cl) and total carbonate (CO_3) were analysed from unacidified samples. The samples for silica (SiO_2) determination were diluted ten times to prevent polymerization.

3.2 Analytical methods

All chemical analyses were carried out in duplicate. The concentration of total carbonate (CO_3), hydrogen sulphide (H_2S) and the pH of the water were analysed on the sampling day. The analytical methods and procedures are presented in Table 1 and the results of the analyses in Tables 2, 3 and 4.

At the UNU training course in Iceland, sampling was demonstrated and some analysis carried out. Some of the analytical procedures differ from the methods given in Table 1. The procedures presented at UNU for total carbonate (CO_3), hydrogen sulphide (H_2S), sulphate (SO_4), silica (SiO_2) and pH measurement may be particularly useful for geothermal waters. The details of the methods and analytical procedures are described in Appendix 1 (A-Q).

TABLE 1: Analytical methods

Components	Method
pH	Glass-electrode and pH-meter.
CO_2	Titration with 0.1N hydrochloric acid (HCl) using pH-meter to indicate end point.
H_2S	Back titration with 0.02N sodium thiosulphate ($Na_2S_2O_3$) in acid solution by adding concentrated hydrochloric acid (HCl) and excess 0.02N iodine (I_2).
Na	Atomic Absorption Spectrophotometer.
K	do
Ca	do
Mg	do
Mn	do
Cl	Chloride sensitive electrode and Mohr titration using 0.1N silver nitrate ($AgNO_3$) solution.
F	Fluoride sensitive electrode.
SiO_2	Molybdenum blue method.
Fe	Phenanthroline method.
SO_4	Gravimetric method involving precipitation with barium.
TDS	Evaporation and weighing.

4 CHEMICAL CHARACTERISTICS OF THE GEOTHERMAL WATERS

The water compositions in each geothermal field have their own characteristics depending on the residence time of the water, the rate of leaching of components from the rocks, the fluid flow into the system and the rate of formation of secondary minerals. Cooling due to boiling, conduction and dilution as well as degassing cause the chemistry of surface discharges to deviate from the composition of the thermal water in the reservoir. In the three geothermal fields which have been studied (see the data in Tables 2, 3, and4), the water has high carbonate as well as high hydrogen sulphide content and a pH generally between 8 to 9.5 (measured at 25°C). The main components are sodium (Na), potassium (K), calcium (Ca), magnesium (Mg) and sulphate (SO_4) which all follow the same pattern. The major cation is sodium (Na). Calcium (Ca), magnesium (Mg) and iron (Fe) occur in higher concentrations in cold water than in the thermal water.

Fluoride (F) and particularly the chloride (Cl) content is very low. The silica (SiO_2) concentrations are two times higher in the area CM4 than in the areas CM2 and CR6.

Arnorsson et al., (1983a) described that the low temperature geothermal areas in the Tertiary basalts in Iceland are very low in chloride (Cl) compared with water issuing from acid volcanic rocks. The fluoride (F) concentration follow the same trend i.e. they are low in basaltic rocks and high in acidic rocks.

5 DATA PROCESSING

The chemical data from the three geothermal fields, CM2, CR6, and CM4, were interpreted. The mean and standard deviation of chemical analyses taken both in May and June 1983 from the areas CM2 and CR6 were compared by statistical methods (Appendix 2) in order to see the correlation between water analyses during each one-month period. It was found that no significant deviation exists between the data taken in May and June, respectively. Therefore, the data from May only were chosen for further calculation and interpretation.

The computer programmes WATCH5 and WATCH3 (Arnorsson and Svavarsson, 1985 and Arnorsson et al., 1982) were used to interpret the chemical analyses of the geothermal water. The programme WATCH5 was used to calculate chemical geothermometry temperatures on the basis of the analyses. A choice of reference temperatures to be used in the programme is possible including those of equilibrium with quartz, chalcedony, or NaK-feldspar, or any arbitrary temperature such as the discharge temperature.

The programme WATCH3 computes the chemical composition of geothermal water and steam, aqueous speciation, some geothermometry temperatures, gas pressures, redox equilibria as well as the state of saturation with respect to selected minerals all based on a given chemical analysis of geothermal water at the surface (Svavarsson, 1981).

The WATCH3 programme is exclusively used for chemical analyses of water from boiling springs. If, on the other hand, the water is assumed not to have boiled before sampling, the programme is called WATCH2. The programme is run at a predetermined reference temperatures as the programme WATCH5.

When running the programme for these geothermal fields the quartz equilibrium temperature was used for reference. The waters of the CM4 geothermal field were assumed to have boiled but those of the other two areas not (Appendix 3). Degassing of the hot spring waters in the CM4 field was assumed to be 20% of maximum, i.e. equilibrium degassing.

6 GEOTHERMOMETRY INTERPRETATION

The chemical components dissolved in thermal fluids are valuable in understanding the characteristics of geothermal systems. An important task of geochemistry is to assess the state of equilibrium between solution and alteration minerals in geothermal reservoirs and subsequently to delineate processes affecting equilibrium conditions or departure from them. The phase rule is useful in describing the number of independent variables (degrees of freedom) needed of specify a chemical system at equilibrium. It is found that this number is equal to the number of external variables acting on the system. In the case of geothermal system these variables include temperature, pressure and mobile (incompatible) components. The only major mobile component in geothermal systems is chloride (Ellis and Mahon 1964, 1967). Pressure in the range occurring in geothermal systems (1-200 bars) is not expected to change the equilibrium conditions significantly as the change in partial molal volumes of minerals and solutes is not significant in this pressure range (Helgeson et al., 1978; Ellis and McFadden, 1972; Miller, 1982). Thus, the major element composition of geothermal systems at equilibrium for a given rock composition is controlled by two variables, that is temperature and the mobile component, chloride.

When predicting subsurface temperatures reactions in the upflow are assumed not to modify the composition significantly. Thus, in this respect the analyses of surface water are taken to be representative of the reservoir fluid. Mixing of the thermal water with cold water sometimes occurs which affects the composition of the water emerging at the surface and, therefore, the estimated subsurface temperatures. A number of geothermometers (Appendix 4) have been used to estimate subsurface temperatures, the most important are the quartz and chalcedony geothermometers (Fournier and Rowe, 1966; Mahon, 1966; Arnorsson, 1975; Fournier, 1977), the NaK-felspar geothermometer (Ellis, 1970; Truesdell, 1975; Arnorsson et al., 1983b), the NaKCa and NaKCaMg geothermometers (Fournier and Truesdell, 1973; Paces, 1975; Fournier and Potter II, 1979) and the NaLi-geothermometer (Fouillac and

Michard, 1981). Use of total water composition has recently been developed to facilitate geothermometry interpretation (Arnorsson and Svavarsson, 1985).

6.1 Solute geothermometers

For the evaluation of subsurface temperatures, as a rule, the concentration of a certain component is assumed to be equal to the activity of some aqueous species. The temperature functions in Table 5 (Arnorsson and Svavarsson, 1985), used in the WATCH5 computer programme are, however, based on activities or activity ratios of particular species. When deciding which cation ratios and neutral species concentrations to select as geothermometer, Arnorsson and Svavasrsson (1985) took temperature variations and minimum scatter of the data points to be of first priority.

In the previous section the data processing used to evaluate subsurface temperatures was outlined for the three geothermal fields CM2, CR6, and CM4. Subsurface temperatures estimated by the various solute geothermometers differ somewhat. The mean and standard deviation of individual geothermometry temperatures for each sample were compared by statistical methods (Appendix 2) in order to study their interrelation (Fig. 2).

In the CM2 and CR6 geothermal fields, the CO_2^-, H_2S^-, and HF-temperatures give similar results as shown by the relatively small scatter around the equal temperature curve (Fig. 2B, 2C, 2G). It is concluded, if the system attained equilibrium with quartz, that reactions with respect to these species were similar in the upflow as for quartz. The quartz and CaH temperatures (Fig. 2A, 2D) are slightly below the mean temperature which can be explained by increase in pH by reactions in the upflow and simultaneous ionization of some of the dissolved silica. The pH increase will also cause $H_2SO_4^-$temperatures to be low, which is indeed the case (Fig. 2H). The NaK-temperatures tend to show large scatter and are above the curve. This is probably due to lack of equilibration, at least with respect to felspars. The MgK-temperatures also show a large

scatter on both side of the curve. Magnesium concentrations are very variable in the waters which, I consider, to be due to leaching from the rock in the upflow thus causing erratic MgK-temperatures.

In the CM4 geothermal field,the quartz-, H_2S-, CaH-, NaK-, and H_2SO_4 temperatures are similar to the mean temperature when calculating aqueous speciation at the quartz equilibrium temperature (Fig. 2A, 2C, 2D, 2E). It is concluded, if equilibrium was attained with respect to quartz in the reservoir that reactions affecting the concentrations of the respective species in the upflow were insignificant. CO_2-temperatures are high relative to the mean temperature (Fig. 2B) which may be explained by carbonate leaching in the upflow or that the anticipated degassing accompanying boiling was too high (20%). This is supported by the plot in Fig. 4B which indicates strong supersaturation at the quartz equilibrium temperature. The MgK-temperatures for the CM4 area are lower than the mean. The cause may be that magnesium is leached from the rock in the upflow. The HF-temperatures are not reliable as the temperature function used in the programme is probably invalid for the rocks in the CM4 area.

Evaluation of geochemical data by Arnorsson and Svavarsson, (1985) showed that:

(1) The geothermometry results of hot springs in Iceland show the standard deviation in the range 50-100°C for mixed water.

(2) The mixed waters tend to yield low H_2S-, MgK-, and NaLi-temperatures but high NaK-temperatures.

(3) Surface waters or other waters which have not equilibrated, or only for some components possess characteristics similar to the mixed waters.

The calculated geothermometry results for the CM2, CR6 and CM4 areas are given in Tables 8-10. The main results are as follows:

(A) The standard deviation is in the range 20-40°C. Therefore, it is concluded that the thermal waters are unmixed except may be for sample no. CM4-C. This water possesses some of the typical characteristics of mixed waters. The mixing may have occurred with surface water.

(B) The NaKCa-temperatures are always significantly lower than the NaK-temperature.

(C) The average mean temperature for CM2, CR6, and CM4 areas are 148(b) (138)(c)°C, 148(b) (142)(c)°C, and 168(b) (178)(d)°C, respectively.

The geothermometry interpretation based on total water composition will aid distinguishing equilibriated waters from non-equilibriated and mixed waters and at the same time help substantiating or disproving the validity of the assumption made when applying geothermometers, namely that the water is in equilibrium with minerals at depth. The geothermometer involving Mg yield often temperature differing much from the other geothermeters. In many of the dilute Icelandic geothermal waters this metal occursin concentrations close to the detection limit (by AA) and this may, at least partly, be the cause of the difference.

Footnotes:

b = The results do not include the NaKCA temperature.
c = The results do not include the NaK and NaKCa temperatures.
d = The results do not include the NaKCa and MgK temperatures.

6.2 Cation to proton ratios

As demonstrated by Arnorsson et al., (1983a), the ratios of all cations in geothermal water are fixed at a particular temperature, if an overall chemical equilibrium is attained with geothermal minerals. The correlation of the various major cations to hydrogen ion was arbitrarity selected. The functions in Table 6 describe the temperature dependence of

the major cation to proton ratios. Fig. 3 shows that the data points from areas CM2 and CR6 are slightly above the equilibrium curve at the quartz equilibrium temperature for the $\sqrt{Ca^{+2}/H^+}$, $\sqrt{Mg^{+2}/H^+}$ and Na^+/H^+ activity ratios. On the other hand, the same ratios show larger scatter and plot below the equilibium curve at the discharge temperature. The K^+/H^+ activity ratio also plots, with few exceptions, above the equilibrium curve both at quartz and discharge temperatures. It is concluded, if equilibrium with quartz was attained in the reservoir that equilibria involving cation/proton ratios in the reservoir have been disturbed partly in the upflow. It also appears that $\sqrt{Ca^{+2}/H^+}$ and $\sqrt{Mg^{+2}/H^+}$ activity ratios have changed more during cooling in the upflow than the Na^+/H^+ activity ratio. The main change apparently involves pH increase. The K^+/H^+ ratios depart from the equilibrium curve both at discharge and quartz equilibrium temperatures. The reason is most likely that the waters have not closely approached K-feldspar equilibrium in the reservoir.

In the CM4 geothermal field, the Na^+/H^+, K^+/H^+, $\sqrt{Ca^+/H^+}$ and $\sqrt{Mg^{+2}/H^+}$ activity ratios show a large scatter around the equilibrium curve at the quartz equilibrium temperature. At discharge temperatures they plot, on the other hand, always somewhat above the equilibrium curve. The variation of the ratios is probably affected by boiling and degassing in the upflow which causes the water pH increase.

6.3 Mineral solubilities

Fig. 4 shows the state of anhydrite, calcite, and fluorite saturation in the water from the CM2, CR6 and CM4 areas. The solubility product equations are given by Arnorsson et al., (1982) (Table 7). The waters are undersaturated with respect to anhydrite at both the quartz equilibrium temperature and discharge temperature. The degree of undersaturation increases when temperature decreases. The mobility of sulphate in the water may be controlled by the following reaction, Arnorsson et al., (1983a):

$$H_2S + 4H_2O = SO_4^{--} + 2H^+ + 4H_2$$

The water from all the areas calculate to be calcite supersaturated, not only at the quratz equilibrium temperature but also at discharge temperature. The reason for the apparent calcite supersaturation may be that the pH of the water has increased from the time of collection to the time of analysis. The degassing of the water in the CM4 area may not be as extensive as assumed for the computer calculations. Water sample no. CM4-C calculates to be a little undersaturated at the quartz equilibrium temperature but saturated at the discharge temperature. It is concluded that re-equilibration has occurred in the upflow most likely by leaching of calcium from the rock. Near the surface degassing may cause conductively cooled calcite undersaturated water to become saturated.

The waters are fluorite undersaturated at the quartz equilibrium temperature but less so at discharge temperature.

7 DISCUSSION AND CONCLUSIONS

The relation between the solute geothermometry temperatures tend to be different for boiled unmixed waters and warm mixed waters. In warm mixed waters the NaK-temperatures are equal to or higher than the quartz temperatures but in boiled unmixed waters quartz temperatures tend to be higher than the NaK-temperatures. Leaching seems to govern the major cation distribution in mixed waters which cause the NaK-temperatures to be invalid as well as the NaKCa-temperatures. Arnorsson et al., (1983a, 1983b) showed that each of the two cation ratios which constitute the NaKCa geothermometer (Na/K and √Ca/Na) are determined by water temperature alone. Application of this geothermometer, therefore, involves the addition of two temperature dependent ratios. For equilibrated gethermal waters, which have cooled by conduction in upflow zone, estimation of underground temperatures by the NaKCa-temperature is probably more conservative than estimation by the NaK geothermometer, as the ratio √Ca/Na appears to respond faster to cooling than the Na/K ratio. A disadvantage of the NaKCa geothermometer is that calcium may precipitate as calcite in significant amounts in upflow zones where boiling takes place. Such precipitation would yield high temperature estimates.

In low temperature fields the approximation to take analysed silica to represent H_4SiO_4 may not be satisfactory as the pH can be as high as 10. In high temperature fields the deep water pH tends to be near neutral but boiling and degassing in the upflow causes the water pH to increase and some silica ionization occurs. However, in every case, it is a good approximation, when temperatures exceed 200°C, to take analysed silica concentration to present undissociated silica (H_4SiO_4).

The concentrations of neutral aqueous species and cation to proton ratios are fixed at a particular temperature for a chemical system like a geothermal at equilibrium and with a fixed composition excluding, however, chloride which is mobile. The solubility of the equilibrating minerals determine individual species concentrations and ratios. This theoretical background is very useful for the predic-

tion of deposition for certain minerals when the geothermal water cools.

In areas CM2, CR6, and CM4 most of the solute geothermometry temperatures show small scatter around the mean geothermometry temperature but a few fall slightly below the mean at the quartz equilibrium temperature. The cation to proton activity ratios fit well with the curve. Thus, it is concluded that these waters have equilibrated with quartz in the reservoir.

The mean subsurface temperatures for areas CM2, CR6 and CM4 are 148(b) (138)(c)°C, 148(b) (142)(c)°C and 168(b) (178)(d)°C standard deviations from the mean being only 6(b) (6)(c)°C, 4(b) (5)(c)°C and 13(b) (16)(d)°C, respectively. The waters from areas CM2 and CR6 have similar subsurface temperatures.

All the waters are undersaturated with respect to anhydrite and fluorite but super saturated with respect to calcite.

The scatter of all data points varies for different activity ratios and concentrations. It is thought that boiling, precipitation and reactions with the rocks in the upflow zone are responsible.

The validity of the solute geothermometry results are affected by reaction in the upflow zone and departure from equilibrium in the reservoir. Evaluation of the water compositions in surface springs may be useful in visualizing scaling and enviromental aspects that could accompany exploitation.

Footnotes

b = The results do not include the NaKCa-temperature.
c = The results do not include the NaK and NaKCa-temperatures.
d = The results do not include the NaKCa and MGK-temperatures.

8 RECOMMENDATIONS

The following recommendations for further geochemical studies are considered valuable for assessing the characteristics of geothermal resources in Thailand. They are based on my work in Iceland, both interpretation in this report and other training.

(1) In order to obtain reliable data on pH, carbonate and hydrogen sulphide in water, samples should be collected into a gas sampling bulb and analysed on the day of collection. Details of sampling and analytical procedures are given in Appendix 1.

(2) The silica and sulphate should be analysed by the green silico-molybdate complex method and titration with barium perchlorate using thorin as indicator, respectively. These methods are rapid and have high accuracy (see Appendix 1).

(3) Additional elements like, lithium, rubidium, boron and aluminium should be analysed to improve interpretation.

(4) Gas samples, should be collected from the hot springs and analysed for components like, carbon dioxide, hydrogen sulphide, hydrogen, oxygen, nitrogen, argon and methane.

(5) Computer facilities should be made use of to evaluate subsurface temperatures and study mineral/solution equilibria from analyses of waters (see Appendix 3).

(6) It is desirable to select a prospective area for drilling of shallow wells. This would allow direct comparison of measured and geothermometry temperatures and facilitate geochemical interpretation in other areas.

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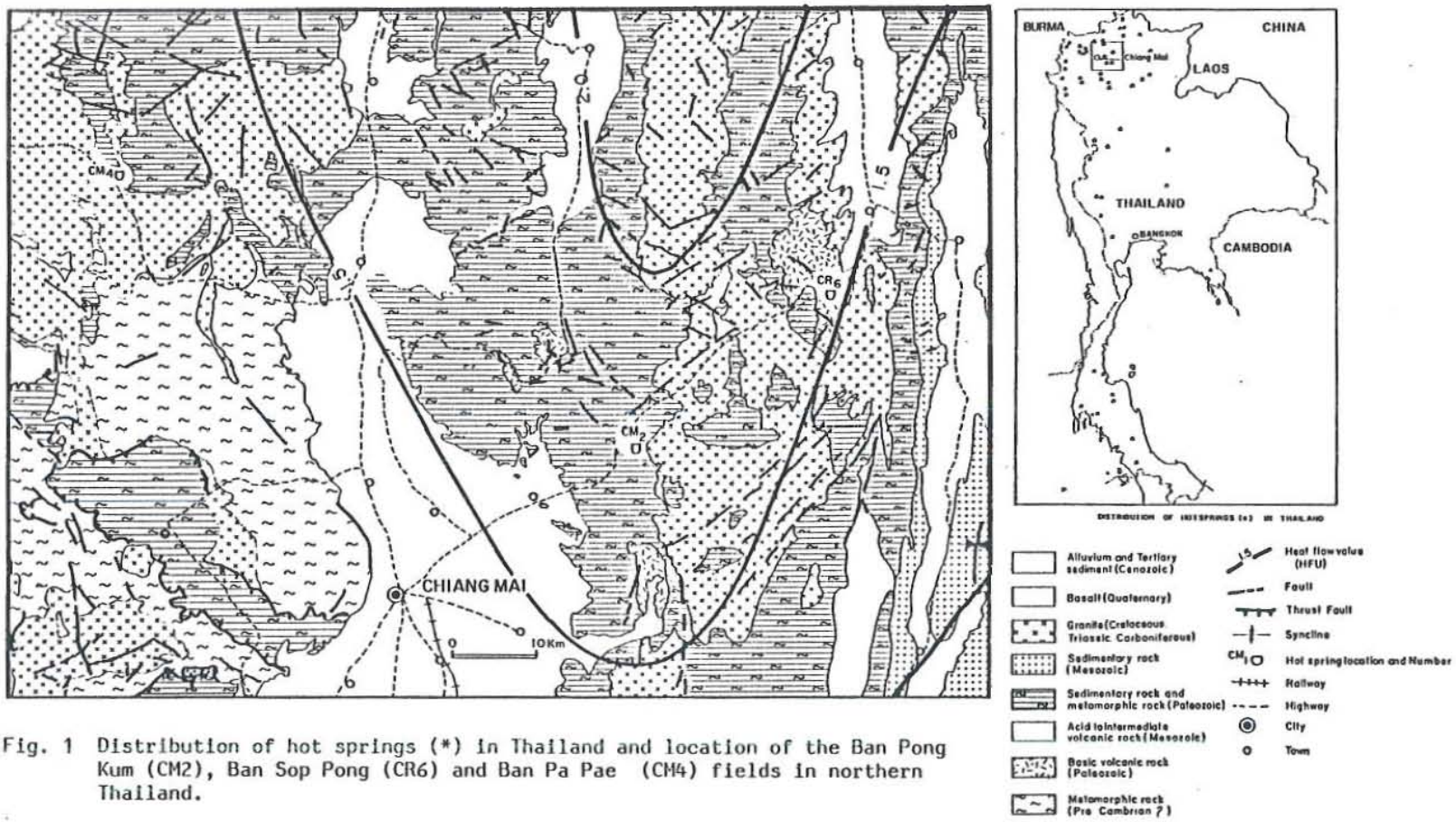


Fig. 1 Distribution of hot springs (*) in Thailand and location of the Ban Pong Kum (CM2), Ban Sop Pong (CR6) and Ban Pa Pae (CM4) fields in northern Thailand.

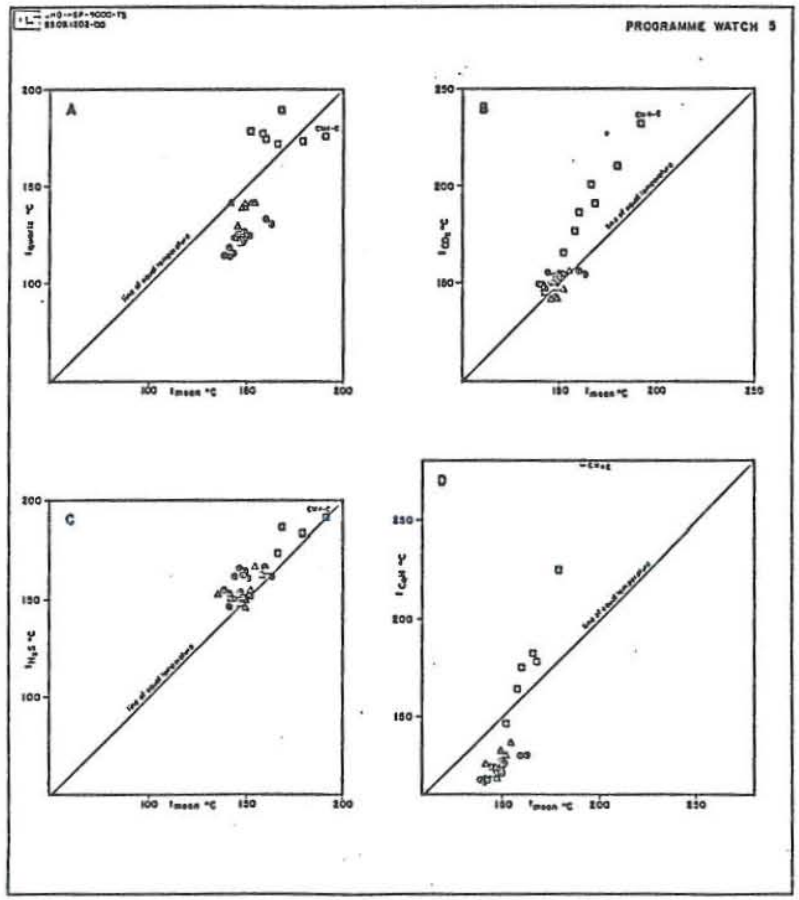


Fig. 2a Relation between quartz, CO_2, H_2S and CaH temperatures and mean geothermometry temperature: Circles, triangles and squares represent hot spring areas CM2, CR6 and CM4 respectively.

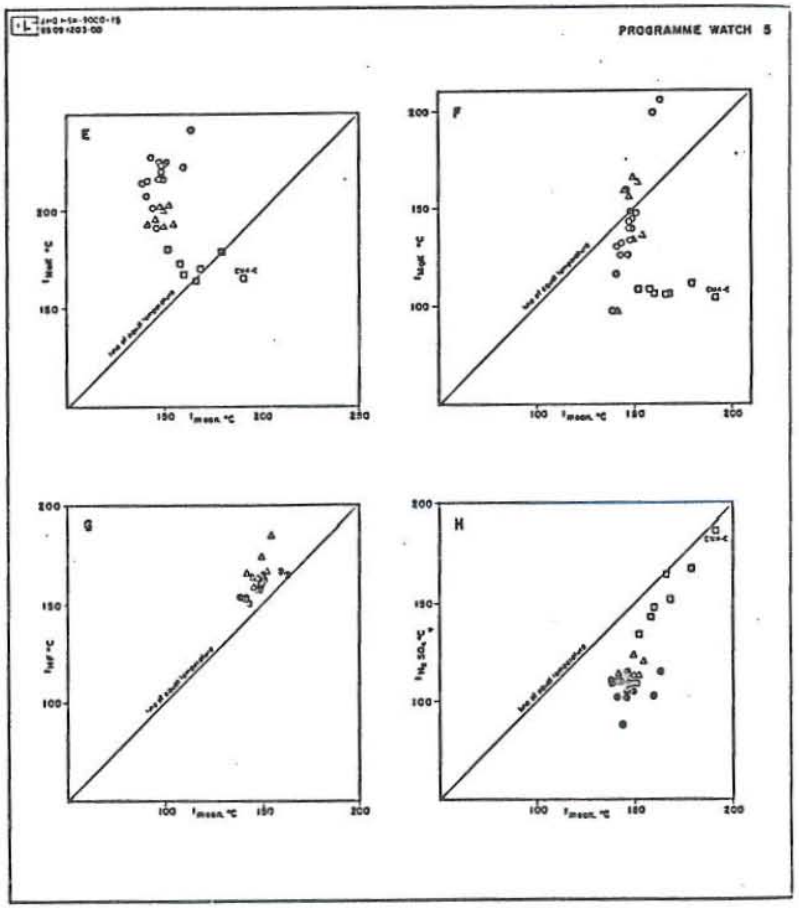


Fig. 2b Relation between NaK, MgK, HF and H_2SO_4 temperatures and mean geothermometry temperature: Circles, triangles and squares represent hot spring areas CM2, CR6 and CM4 respectively.

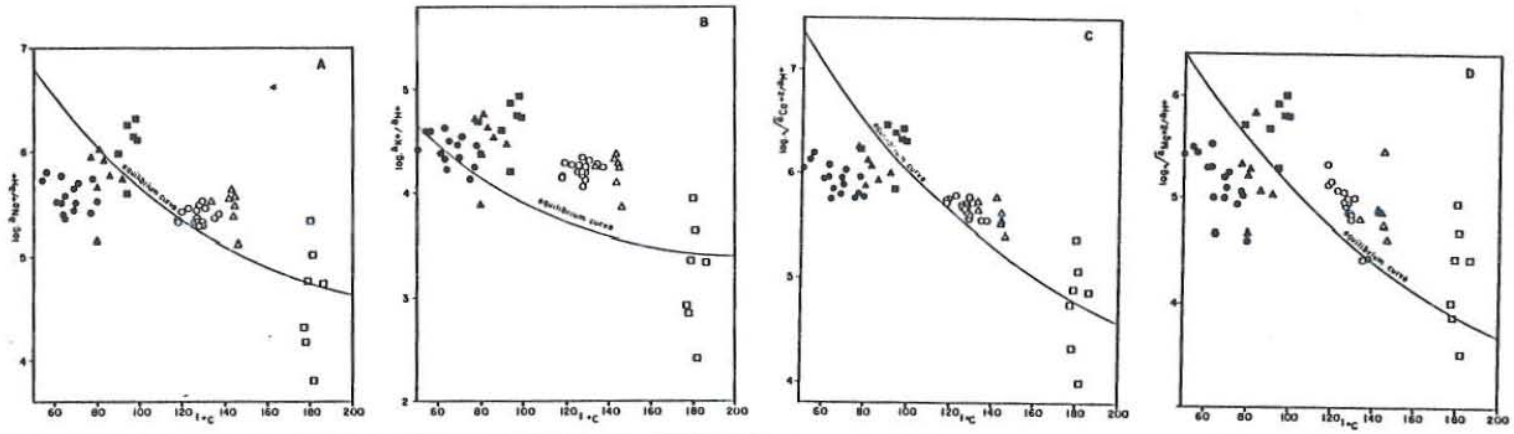


Fig. 3 Relationship between cation/proton activity ratios vs. reference temperature: Circles, triangles and squares represent hot spring areas CM2, CR6 and CM4 respectively. Open symbols indicate quartz reference temperature. Filled symbols correspond with discharge temperature.

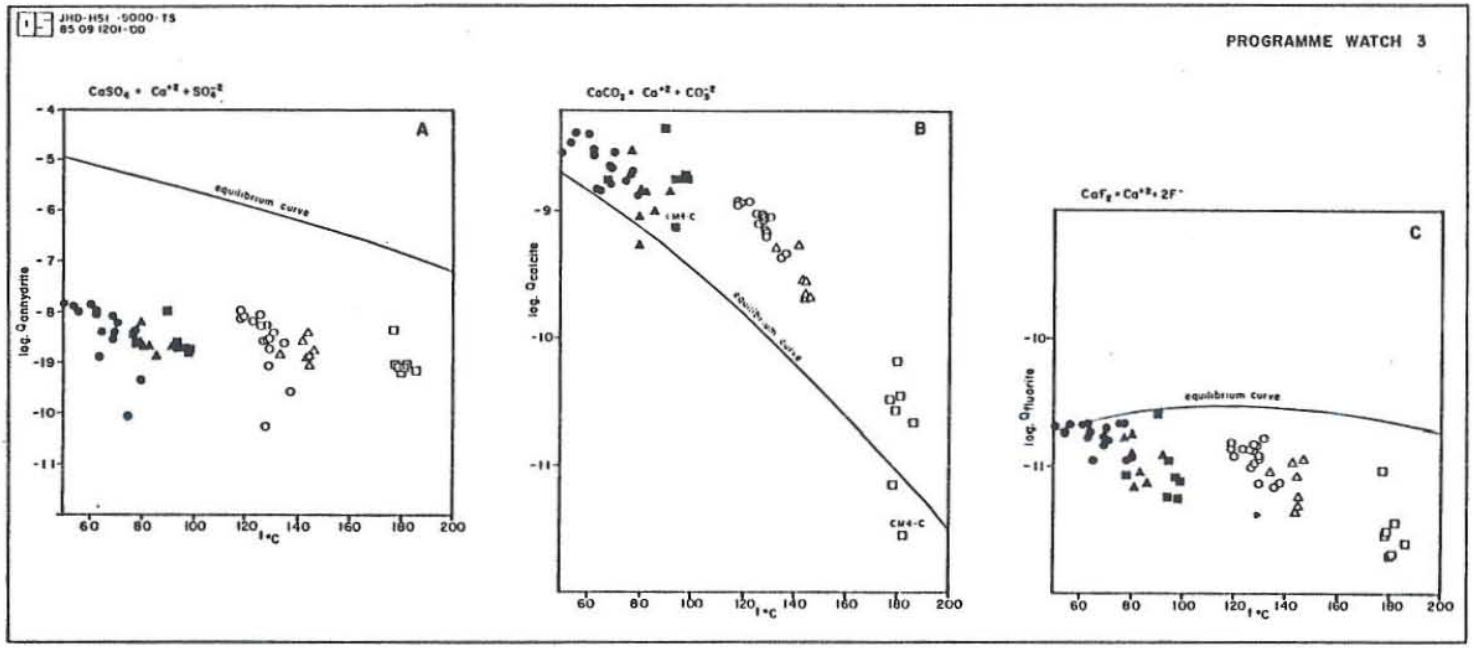


Fig. 4 State of anhydrite, calcite and fluorite saturation: Circles, triangles and squares represent hot spring areas CM2, CR6 and CM4 respectively. Open symbols indicate quartz reference temperature. Filled symbols correspond with discharge temperature.

TABLE 2: Chemical composition of thermal water from Ban Pong Kum hot spring area (CM2) northern Thailand.(concentration in ppm)

Sample no	Temp (°C)	pH 25(°C)	SIO_2	Na	K	Ca	Mg	Fe	Mn	CO_2 (a)	SO_4	H_2S (b)	F	Cl	TDS
CM2A-1	78	8.6	98.4	112	10.0	3.94	0.03	-	0.04	202.68	11.30	6.29	9.50	5.70	480
CM2A-2	75	8.0	91.1	108	10.8	7.63	0.10	-	0.09	187.53	0.10	9.64	8.93	5.10	450
CM2A-3	70	8.2	91.1	109	12.4	6.81	0.10	0.21	0.08	194.74	5.60	6.71	9.12	4.60	450
CM2A-4	64	8.0	92.8	109	12.4	6.06	0.10	0.08	0.09	183.92	1.90	11.32	9.12	3.30	460
CM2A-5	63	8.5	94.1	113	13.6	5.63	0.09	0.15	0.08	196.91	14.60	5.87	9.31	3.30	460
CM2A-6	69	8.1	94.1	108	13.2	6.00	0.08	-	0.05	188.25	4.30	9.64	8.93	3.30	460
CM2B-6	80	8.3	111.0	115	13.6	4.25	0.01	0.13	0.04	193.30	1.00	13.40	9.12	4.10	480
CM2B-7	65	8.3	106.0	106	14.8	3.94	0.01	0.19	0.05	181.76	9.30	10.50	8.93	5.10	460
CM2C-4	49	8.2	76.4	98.6	11.2	7.70	0.25	0.03	0.09	180.32	17.70	6.71	8.36	4.10	420
CM2C-6	63	8.2	76.4	100	11.2	8.13	0.62	0.08	0.24	179.60	11.50	7.55	8.55	3.30	420
CM2C-9	54	8.4	79.6	102	12.8	6.75	0.21	0.13	0.08	186.81	16.10	6.29	8.55	3.60	420
CM2C-10	56	8.5	85.6	106	11.2	7.20	0.13	0.08	0.05	181.76	11.90	5.03	8.93	3.60	450
CM2C-11	71	8.5	99.9	107	12.8	6.00	0.09	0.14	0.06	201.23	9.70	6.29	9.12	4.10	440
CM2C-12	77	8.1	91.1	109	12.8	7.88	0.14	0.13	0.05	187.53	4.70	10.90	8.93	3.80	420
CM2C-13	69	8.4	91.1	109	12.4	5.20	0.09	0.03	0.05	196.91	14.80	7.55	9.12	3.30	450
CM2C-14	61	8.2	81.1	101	12.4	7.50	0.02	0.06	0.05	186.09	15.80	7.55	8.74	4.10	420
CM2W*	27	7.1	21.2	36.4	8.8	7.38	1.60	1.60	0.38	90.88	6.20	0.84	1.69	3.80	180

a = Total carbonate ; b = Total hydrogen sulphide

* = Non thermal water

TABLE 3: Chemical composition of thermal water from Ban Sop Pong hot spring area (CR6) northern Thailand (concentration in ppm)

Sample no.	Temp (°C)	pH 25(°C)	SIO_2	Na	K	Ca	Mg	Fe	Mn	CO_2 (a)	SO_4	H_2S (b)	F	Cl	TDS
CR6A-1	92	8.9	109	90.9	8.40	3.22	0.02	0.08	0.04	146.42	6.20	9.22	11.0	5.90	420
CR6A-2	80	8.7	126	95.5	8.60	2.60	0.07	1.10	0.05	126.22	21.00	5.45	11.80	7.00	450
CR6A-3	86	8.9	132	91.4	8.92	1.91	0.02	0.13	-	148.58	6.80	8.80	11.00	5.10	420
CR6A-4	83	9.0	135	97.7	8.60	2.20	0.40	0.43	0.04	150.74	9.70	7.13	11.40	6.40	430
CR6A-5	81	9.1	136	96.8	9.00	1.82	0.02	0.13	0.01	152.19	11.50	6.29	11.20	5.70	450
CR6B-1	77	9.0	129	95.5	9.24	4.06	0.03	0.03	0.05	146.42	9.50	6.29	11.20	5.90	430
CR6B-2	80	7.9	126	89.5	8.20	4.13	0.05	0.10	0.01	133.43	5.60	10.10	10.60	6.40	430
CR6-S*	30	7.1	5.99	5.90	4.20	7.50	2.80	1.88	0.36	25.97	2.50	-	0.29	5.10	80

TABLE 4: Chemical composition of thermal water from Ban Pa Pae hot spring area (CM4) northern Thailand (concentration in ppm)

Sample no.	Temp (°C)	pH 25(°C)	SIO_2	Na	K	Ca	Mg	Fe	Mn	CO_2 (a)	SO_4	H_2S (b)	F	Cl	TDS
CM4-A	99	9.5	272.80	82	5.6	2.3	-	0.08	-	119.70	10.00	8.8	11.50	1.0	425
CM4-B	94	9.6	256.70	81	5.6	1.7	-	0.05	-	122.70	15.00	4.0	12.00	1.0	425
CM4-C	94	8.9	243.90	81	5.6	2.3	-	0.08	-	124.15	10.00	2.4	12.00	1.0	430
CM4-D	98	9.7	272.80	81	5.6	1.8	-	0.10	-	121.15	13.00	3.2	12.00	1.0	415
CM4-E	97	9.5	240.70	83	5.6	2.2	-	0.10	-	119.70	11.00	2.8	12.00	1.0	435
CM4-F	90	9.3	228.90	79	5.4	6.9	-	0.10	-	110.73	16.00	2.4	11.00	1.0	425
CM4-G	78	9.2	231.00	81	6.5	2.1	-	0.25	-	116.67	10.00	3.2	11.00	1.0	430
CM4-S*	18	8.2	26.7	7.0	1.5	4.2	-	0.23	-	25.45	7.00	0.2	0.20	1.0	80

a = Total carbonate; b = Total hydrogen sulphide

* = Stream water

TABLE 5. Temperature functions for solute geothermometers.

Geothermometer	log species/ratio	Temperature function, °K	$\bar{M}^a$	σ^a
SiO_2	$^mH_4SiO_4$	= -0.588 -0.00441•T -1515.21/T +1.3470•logT	9	7
CO_2	$^mH_2CO_3$	= -1.794 -0.00510•T -4469.63/T +4.1414•logT	10	9
H_2S	^mH_2S	= -1.678 -0.00355•T -5071.05/T +3.8889•logT	10	11
NaK	$^aNa^+/^aK^+$	= -0.692 +908/T	7	6
NaRb	$^aNa^+/^aRb^+$	= +1.318 +1272/T	19	16
NaLi	$^aNa^+/^aLi^+$	= +0.161 +1201/T	27	22
CaH	$^a\sqrt{Ca^{+2}}/^aH^+$	= +1.733 +0.01117•T +3890.51/T -3.9977•logT	9	7
MgK	$^a\sqrt{Mg^{+2}}/^aK^+$	= -0.00396•T +978.33/T	27	21
HF	^mHF	= -5.262 -0.03511•T -7964.11/T +12.1022•logT	10	8
H_2SO_4	$^mH_2SO_4$	= -6.436 -0.03906•T -13335.68/T +14.7958•logT	8	7

[a]Mean and standard deviations of data points from the reported functions, respectively

Table 6. Equations describing the temperature dependence of cation/proton ratios and uncharged species concentrations in geothermal drill hole discharges

Species/ion ratio (moles/kg)	Temperature function				Log species/ion ratio: Mean deviation	Log species/ion ratio: S.D.
$\log H_4SiO_4^\circ$	−0.588	$-0.00441T$	$-1515.21/T$	$+1.3470\log T$	0.06	0.05
$\log H_2CO_3^\circ$	−1.794	$-0.00510T$	$-4469.63/T$	$+4.1414\log T$	0.30	0.26
$\log H_2S^\circ$	−1.678	$-0.00355T$	$-5071.05/T$	$+3.8889\log T$	0.36	0.33
$\log H_2SO_4^\circ$	−6.436	$-0.03906T$	$-13335.68/T$	$+14.7958\log T$	0.57	0.48
$\log HF^\circ$	−5.262	$-0.03511T$	$-7964.11/T$	$+12.1022\log T$	0.32	0.28
$\log Na^+/H^+$	2.694	$+0.02023T$	$+4243.47/T$	$-6.2069\log T$	0.14	0.12
$\log K^+/H^+$	2.505	$+0.01971T$	$+3325.71/T$	$-5.7814\log T$	0.12	0.09
$\log\sqrt{Ca^{2+}}/H^+$	1.733	$+0.01117T$	$+3890.51/T$	$-3.9977\log T$	0.17	0.12
$\log\sqrt{Mg^{2+}}/H^+$	1.816	$+0.01078T$	$+3727.48/T$	$-4.1640\log T$	0.34	0.27
$\log\sqrt{Fe^{2+}}/H^+$	−4.696	$-0.04273T$	$-1011.46/T$	$+10.8032\log T$	0.18	0.17
$\log Al(OH)_4^-/OH^-$	−3.407	$-0.02364T$	$-3417.36/T$	$+7.8426\log T$	0.21	0.12

TABLE 7: Equations describing the temperature dependence of mineral solubilities

MINERAL	REACTION	TEMPERATURE FUNCTION (°K)
401 ADULARIA[c]	$KAlSi_3O_8 + 8H_2O = K^+ + Al(OH)_4^- + 3H_4SiO_4^\circ$	+38.85 −0.0458T −17260/T +1012722/T^2
402 LOW-ALBITE	$NaAlSi_3O_8 + 8H_2O = Na^+ + Al(OH)_4^- + 3H_4SiO_4^\circ$	+36.83 −0.0439T −16474/T +1004631/T^2
403 ANALCIME	$NaAlSi_2O_6 \cdot H_2O + 5H_2O = Na^+ + Al(OH)_4^- + 2H_4SiO_4^\circ$	+34.08 −0.0407T −14577/T +970981/T^2
404 ANHYDRITE	$CaSO_4 = Ca^{+2} + SO_4^{-2}$	+6.20 −0.0229T −1217/T
405 CALCITE[d]	$CaCO_3 = Ca^{+2} + CO_3^{-2}$	+10.22 −0.0349T −2476/T
406 CHALCEDONY[e]	$SiO_2 + 2H_2O = H_4SiO_4^\circ$	+0.11 −1101/T
407 Mg-CHLORITE	$Mg_5Al_2Si_3O_{10}(OH)_8 + 10H_2O = 5Mg^{+2} + Al(OH)_4^- + 3H_4SiO_4^\circ + 8OH^-$	−1022.12 −0.3861T +9363/T +412.46logT
408 FLUORITE[f]	$CaF_2 = Ca^{+2} + 2F^-$	+66.54 −4318/T −25.47logT
409 GOETHITE[g]	$FeOOH + H_2O + OH^- = Fe(OH)_4^-$	−80.34 +0.099T +20290/T −2179296/T^2
410 LAUMONTITE	$CaAl_2Si_4O_{12} \cdot 4H_2O + 8H_2O = Ca^{+2} + 2Al(OH)_4^- + 4H_4SiO_4^\circ$	+65.95 −0.0828T −28358/T +1916098/T^2
411 MICROCLINE	$KAlSi_3O_8 + 8H_2O = K^+ + Al(OH)_4^- + 3H_4SiO_4^\circ$	+44.55 −0.0498T −19883/T +1214019/T^2
412 MAGNETITE	$Fe_3O_4 + 4H_2O = 2Fe(OH)_4^- + Fe^{+2}$	−155.58 +0.1658T +35298/T −4258774/T^2
413 Ca-MONTMOR.[c]	$6Ca_{0.167}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 60H_2O + 12OH^- = Ca^{+2} + 14Al(OH)_4^- + 22H_4SiO_4^\circ$	+30499.49 +3.5109T −1954295/T +125536640/T^2 −10715.66logT
414 K-MONTMOR.[c]	$3K_{0.33}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 30H_2O + 6OH^- = K^+ + 7Al(OH)_4^- + 11H_4SiO_4^\circ$	+15075.11 +1.7346T −967127/T +61985927/T^2 −5294.72logT
415 Mg-MONTMOR.[c]	$6Mg_{0.167}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 60H_2O + 12OH^- = Mg^{+2} + 14Al(OH)_4^- + 22H_4SiO_4^\circ$	+30514.87 +3.5188T −1953843/T +125538830/T^2 −10723.71logT
416 Na-MONTMOR.[c]	$3Na_{0.33}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 30H_2O + 6OH^- = Na^+ + 7Al(OH)_4^- + 11H_4SiO_4^\circ$	+15273.90 +1.7623T −978782/T +62805036/T^2 −5366.18logT
417 MUSCOVITE	$KAl_3Si_3O_{10}(OH)_2 + 10H_2O + 2OH^- = K^+ + 3Al(OH)_4^- + 3H_4SiO_4^\circ$	+6113.68 +0.6914T −394755/T +25226323/T^2 −2144.77logT
418 PREHNITE	$Ca_2Al_2Si_3O_{10}(OH)_2 + 10H_2O = 2Ca^{+2} + 2Al(OH)_4^- + 2OH^- + 3H_4SiO_4^\circ$	+90.53 −0.1298T −36162/T +2511432/T^2
419 PYRRHOTITE	$8FeS + SO_4^{-2} + 22H_2O + 6OH^- = 8Fe(OH)_4^- + 9H_2S$	+3014.68 +1.2522T −103450/T −1284.86logT
420 PYRITE	$8FeS_2 + 26H_2O + 10OH^- = 8Fe(OH)_4^- + SO_4^{-2} + 15H_2S$	+4523.89 +1.6002T −180405/T −1860.33logT
421 QUARTZ[h]	$SiO_2 + 2H_2O = H_4SiO_4^\circ$	+0.41 −1309/T (0–250°C); +0.12 −1164/T (180–300°C)
422 WAIRAKITE	$CaAl_2Si_4O_{12} \cdot 2H_2O + 10H_2O = Ca^{+2} + 2Al(OH)_4^- + 4H_4SiO_4^\circ$	+61.00 −0.0847T −25018/T +1801911/T^2
423 WOLLASTONITE	$CaSiO_3 + 2H^+ + H_2O = Ca^{+2} + H_4SiO_4^\circ$	−222.85 −0.0337T +16258/T −671106/T^2 +80.68logT
424 ZOISITE	$Ca_2Al_3Si_3O_{12}(OH) + 12H_2O = 2Ca^{+2} + 3Al(OH)_4^- + 3H_4SiO_4^\circ + OH^-$	+106.61 −0.1497T −40448/T +3028977/T^2
425 EPIDOTE	$Ca_2FeAl_2Si_3O_{12}(OH) + 12H_2O = 2Ca^{+2} + Fe(OH)_4^- + 2Al(OH)_4^- + 3H_4SiO_4^\circ + OH^-$	−27399.84 −3.8749T +1542767/T −92778364/T^2 +9850.38logT
426 MARCASITE[i]	$8FeS_2 + 26H_2O + 10OH^- = 8Fe(OH)_4^- + SO_4^{-2} + 15H_2S$	+4467.61 +1.5879T −169944/T −1838.45logT

[a]If not otherwise specified data for minerals and aqueous species are from HELGESON et al. (1978) and HELGESON (1969). [b]Data on $Al(OH)_4^-$ and $Fe(OH)_4^-$ are from ARNÓRSSON et al. (1982a) and GUNNLAUGSSON and ARNÓRSSON (1982) respectively. [c]Thermodynamic data on adularia are from HELGESON (1969). [d]Data on the enthalpy and entropy of calcium ion at 25°C are from ROBIE et al. (1978). [e]ARNÓRSSON et al. (1982b). Their empirical solubility function is very similar to the experimental solubility data of FOURNIER (1977). [f]NORDSTROM and JENNE (1977). [g]LANGMUIR (1971). [h]MOREY et al. (1962), KENNEDY (1950). [i]NAUMOV et al. (1971).

TABLE 8: Geothermometry results for Ban Pong Kum hot spring area (CM2) northern Thailand

Location	Meas.	NaKCa	Qtz.	CO_2	H_2S	NaK	CaH	MgK	HF	H_2SO_4	$\bar{M}^{(a)}$	$\delta^{(a)}$
											(b) (c)	(b) (c)
CM2A-1	78	182	126	150	150	192	124	159	158	112	146(140)	25(19)
CM2A-2	75	181	123	155	162	202	124	132	164	88	144(135)	34(27)
CM2A-3	70	190	123	153	154	217	122	139	161	109	148(138)	33(20)
CM2A-4	64	191	124	155	165	217	127	139	165	105	150(140)	34(23)
CM2A-5	63	196	124	150	150	224	121	148	158	113	149(138)	35(18)
CM2A-6	69	195	125	154	161	225	126	147	163	109	151(141)	35(21)
CM2B-6	80	197	133	156	167	223	130	199	167	103	160(151)	39(31)
CM2B-7	65	206	131	154	162	242	130	205	165	115	163(151)	42(29)
CM2C-4	49	186	114	149	153	216	118	116	153	112	141(131)	35(20)
CM2C-6	63	185	114	149	155	214	117	97	154	109	139(128)	38(24)
CM2C-9	54	194	115	147	150	228	117	126	151	110	143(131)	38(18)
CM2C-10	56	184	119	147	147	208	116	130	153	110	141(132)	31(17)
CM2C-11	71	193	127	152	151	224	121	144	159	112	149(138)	35(18)
CM2C-12	77	190	123	154	163	220	122	133	162	109	148(138)	35(22)
CM2C-13	69	192	122	151	154	217	122	143	158	113	147(138)	33(18)
CM2C-14	61	191	121	152	156	225	120	126	159	115	147(136)	36(19)
$\hat{M}^{(a)}$		191	123	152	156	218	122	143	159	109	148(138)	
$\delta^{(a)}$		6	5	3	6	11	4	27	5	6	6 (6)	

a = Mean and standard deviations of geothermometry results

b = The results do not include the NaKCa temperature

c = The results do not include the NaK and NaKCa temperatures

TABLE 9: Geothermometry results for Ban Sop Pong hot spring area (CR6) northern Thailand

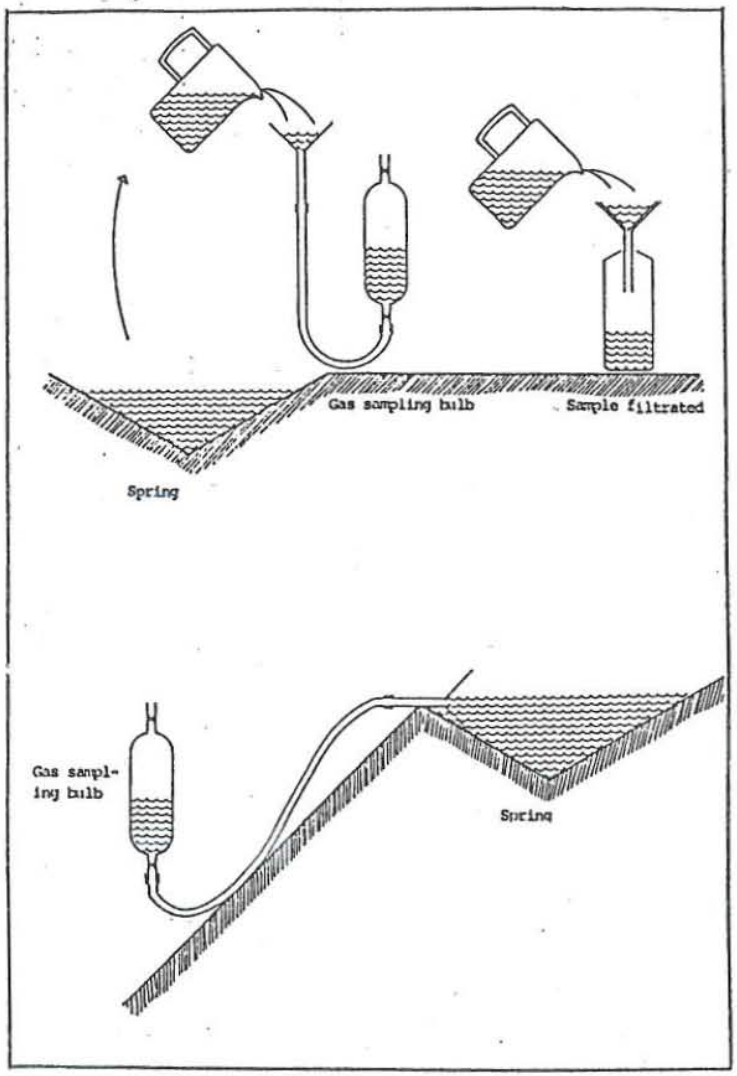
Location	Meas.	NaKCa	Qtz	CO_2	H_2S	NaK	CaH	MgK	HF	H_2SO_4	$\bar{M}$(a)	δ(a)
											(b) (c)	(b) (c)
CR6A-1	92	181	130	141	153	196	120	159	158	106	145(138)	28(20)
CR6A-2	80	183	140	147	151	192	132	134	174	123	149(143)	23(17)
CR6A-3	86	190	141	146	155	203	130	163	167	113	152(145)	27(19)
CR6A-4	83	184	142	145	150	193	126	97	166	114	142(134)	30(23)
CR6B-1	77	183	139	143	148	202	118	155	162	113	149(142)	27(19)
CR6B-2	80	178	141	156	167	193	137	136	163	112	147(140)	28(19)
M		184	139	146	153	197	127	144	185	120	154(149)	26(22)
δ		4	4	5	7	5	7	24	9	6	4 (5)	

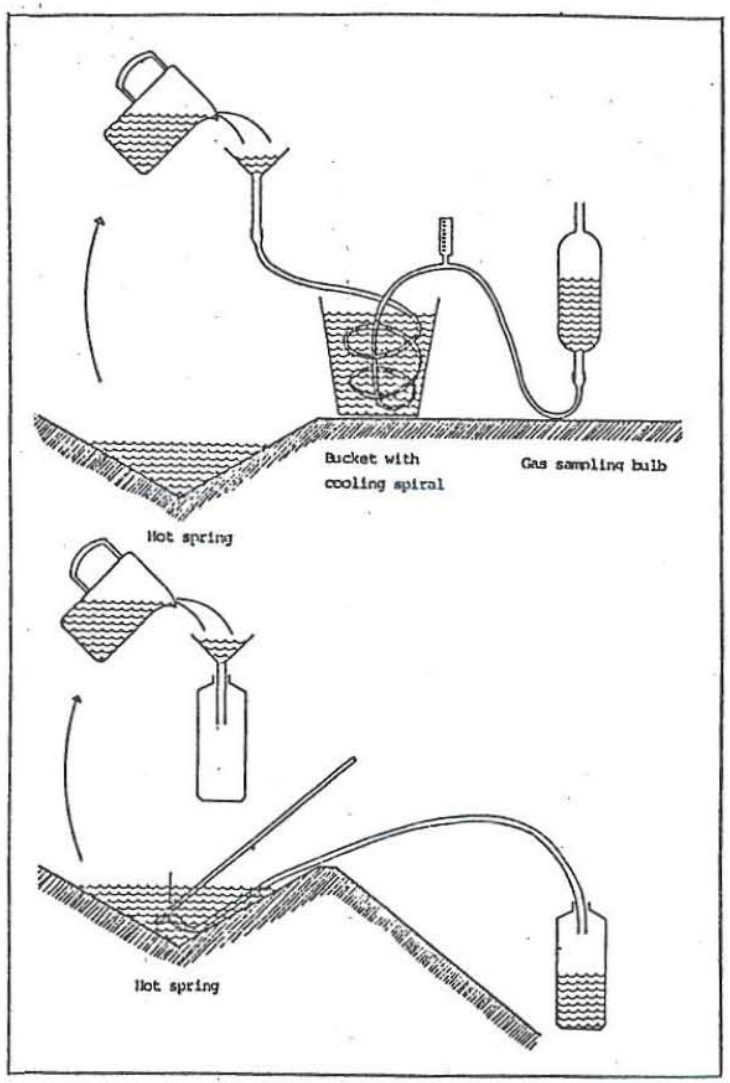
TABLE 10: Geothermometry results for Ban Pa Pae hot spring area (CM4) northern Thailand

Location	Meas.	NaKCa	Qtz	CO_2	H_2S	NaK	CaH	MgK	HF(e)	H_2SO_4	$\bar{M}$(a)	δ(a)
											(b) (d)	(b) (d)
CM4-A	99	167	189	191	187	170	178	106	-	152	168(179)	30(15)
CM4-B	94	170	177	177	163	173	164	108	-	143	158(166)	25(13)
CM4-C	94	167	176	232	192	165	279	104	-	187	191(205)	55(43)
CM4-D	98	169	178	165	152	180	146	108	-	134	152(159)	26(18)
CM4-E	97	167	174	186	165	167	175	106	-	148	160(169)	27(13)
CM4-F	90	157	172	201	174	164	182	105	-	165	166(176)	30(14)
CM4-G	78	176	173	210	184	179	225	111	-	168	179(190)	36(23)
M(a)		168	177	195	174	171	193	107	-	157	168(178)	
δ(a)		6	6	22	15	6	45	2	-	18	13 (16)	

a = Mean and standard deviations of geothermometry results; b = The results do not include the NaKCa temperature;
c = The results do not include the NaK and NaKCa temperatures; d = The results do not include the NaKCa and MgK temperatures;
e = The temperatures are not reliable.

APPENDIX I: Analytical methods





1. Recording of Samples.

One of the most important thing during collection of water samples is good recording. Analysis of water after careful collection procedure is of little use if noone knows where the samples were taken.

For the purpose of keeping good record of samples, it is suitable to use special forn (see pages A-4 and 5. The upper part is for general information, such as number of sample, date of collection, the location of sample, reference to geographical map, and brief description of geological features. The temperature of the spring, and estimated or measured flow rate is also recorded. The lower part of the form is for recording all analytical measurements done during or shortly after collection. This part is used in connection to chapters C and D of this manual.

2. Collection Technique.

For the collection of thermal water from hot springs and drillholes with temperature lower than 100°C the following are required:

1. Polythene tubing 1/4", 5 m long.
2. Polythene can, 0.5 - 1.0 liters.
3. Polythene funnel.
4. Maximum thermometer.
5. Stainless stoel cooling spiral to fit 1/4" tubing.
6. Bucket (10 liters).
7. Gas sampling bulb (250 ml).
8. Polythene bottles for storing the samples.

Various techniques have been developed to collect water from thermal springs, in order to minimize contamination from soil and rocks. Spring with high flow rates and/or wide basins are most easily sampled by scooping up the water with the can. If there is some slope where the water can flow, it is most convenient to use the funnel and the tubing (see lower part of fig. 1 and 2). In some cases, if the pooles are only a few centimeters deep the water can be sucked up using the gas sampling bulb.

The cooling spiral is only necessary for that part of the sample which is stored in the gas sampling bulb, later used for determination of pH, CO_2, and H_2S (see fig. 2). The cooling spiral is made of stainless steel, but cooling spirals made of copper have been used. The latter is not suitable because the copper reacts with the hydrogen sulphide giving low concentration for sulphide during determination. It is desirable to cool the sample down to the storage temperature, where the analysis are done. If the sample is not cooled before it is stored in the gas sampling bulb, volume reduction caused by later cooling will produce low pressure in the bulb and cause degassing. During collection the temperature is measured using maximum thermometer and the water flow is measured or estimated.

3. Treatment of Samples.

It must be garanteed during collection of samples, that the concentration of the elements does not change until the analyses are carried out. The following components often changes during storage: pH, carbonate, hydrogen sulphide, calcium, magnesium, sulphate, nitrate and silica. This can be prevented in the following way:

1. Carbonate, sulphide and pH.

   Carbonate and sulphide degasses during storage and change the pH. To prevent this, part of the sample is cooled and stored in the gas sampling bulb. This is determined within 36 hours, usually the same evening.

2. Sulphate.

   If the concentration of the hydrogen sulphide is high, the sulphide can oxidize to sulphate. To be able to determine sulphate after storage, the sulphide must be precipitated using $Zn(CH_3COO)_2$ solution (20.88 g/l). Two ml of the solution is added to 100 ml of the sample and stored in polythene bottle.

3. Calcium and nitrate.

Ammonium and nitrite may oxidize to nitrate during storage. Oxidation may be prevented by freezing the sample. Calcium and magnesium sometimes precipitates from the water during storage, specially if the carbonate content is high. To prevent this, part of the sample is acidified. One ml conc. HCl is added to 100 ml of sample and then stored in polythene bottle.

4. Silica.

If the silica content is above 100 ppm, it will polimerize. This can be prevented by dilution of the sample if the silica content is expected to be higher than 100 ppm, which simplifies analysis. If this is left, the polymerized silica can be disintergrated by boiling in dilute alkaline solution.

The concentration of other major components are not expected to change during storage. For determination of these elements, 500 ml of sample is stored in a polythene bottle.

Summary of Collection:

1. One gas sampling bulb, cooled to 20-30 °C.
2. 500 ml sample untreated, in polythene bottle.
3. 100 ml sample + 1 ml conc. HCl to polythene bottle.
4. 100 ml sample + 2 ml $Zn(CH_3COO)_2$ to polythene bottle.

VIRKIR
CONSULTING GROUP LTD.

COLLECTION OF WATER SAMPLES FOR CHEMICAL ANALYSIS

COUNTRY	YEAR	MONTH	DATE	NUMBER

LOCALITY (SPRING, WELL)

AREA

REFERENCE MAP | LONGITUDE | LATITUDE

LOCATION

GEOLOGICAL FEATURES

REMARKS

TEMPERATURE °C | FLOW RATE

pH buffer 6.88		Normality of HCl		Gas sampling bulb	
pH buffer 9.22		Normality of $Hg(CH_3COO)_2$		500ml polyethylene bottle	
pH buffer 4.62				100ml + 1 ml conc. HCl	
				100ml + 2ml $Zn(CH_3COO)_2$	

pH/°C meas.	pH/°C corr.	ml sample for CO_2	burette reading I	burette reading II	ΔHCl	ml sample for H_2S	burette reading I	burette reading II	$\Delta mlCH_3COO)_2$
				ppm CO_2				ppm H_2S	

IF FURTHER REMARKS PLEASE USE OTHER SIDE

Determination of pH and carbonate.

Total carbonate is determined by titration with o.1 N HCl from pH 8.2 to 3.8 at 20°C but pH is measured using pH meter.

The following equipment and reagents are required for this determination:

1) portable pH-meter
2) pH electrode
3) saturated KCl solution
4) three small beakers for pH buffers
5) 150 ml beaker for sample
6) 50 ml and 100 ml volumetric flasks
7) thermometer
8) 25 ml burette calibrated at 0.1 ml interval, burette stand and clamp or 2.5 ml micro syringe
9) 1 ml and 5 ml pipettes
10) 0.1 N HCl solution (e.g. titrisol 0.1 N HCl, Merck 9973)
11) Approx. 0.1 N NaOH solution. Dissolve 4 g NaOH in 1 liter of distilled water
12) pH buffers. Phosphate buffer 6.88, borax buffer 9.22 and acetate buffer 4.62
13) distilled water

Procedure:

1) Fill the electrode with KCl solution if necessary.
2) Rinse the electrode with distilled water.
3) Adjust the pH-meter to the 6.88 pH-buffer.
4) Measure the 9.22 and 4.62 buffers and rinse the electrode between measurements with distilled water.
5) Measure 100 ml (50 ml) of sample using the volumetric flask. and put into the 150 ml beaker.
6) Determine the pH and the temperature.
7) Adjust the pH carefully to correct 8.2 value using 0.1 N HCl if the pH is higher than 8.2 but using 0.1 N NaOH if the pH is lower than 8.2.
8) Titrate from pH 8.2 to pH 3.8 using 0.1 N HCl.
9) Record the amount HCl required.
10) Rinse the electrode with distilled water and go to no. 5. Titrate each sample in duplicate.
13) $\text{ppm } CO_2 = \left(\frac{\text{mlHCl} \cdot N \cdot 44000}{\text{ml sample}}\right) - (6.93 + 1.182 \text{ ppm} H_2S + 0.0088 \text{ ppm } SiO_2^{-2})$

The procedure in part 1 - 4 are only made once every time measurements are carried out and are valid for all samples measured at the same time. The measurement of three pH buffers makes it possible to correct for deviation from theoretical behaviour of the electrode. Two methods can be used for these corrections. One involves plotting measured values of the pH-buffers against right values of the buffers and then use the best fit line for correcting the pH of the samples. The other method is to use two buffers (6.88 and 9.22) and calculate correct pH using:

$$\text{pH sample}_{corr.} = 6.88 + \frac{(9.22-6.88)}{\text{buffer } 9.22_{meas.} - 6.88} (\text{pH sample}_{meas.} - 6.88)$$

The values of the pH-buffers varies with temperature. The values 4.62, 6.88 and 9.22 are at 20°C. If the temperature is different the values have to be corrected according to table 1.

TABLE 1.

Changes in pH values of buffers with different temperature.

°C	Phosphate Buffer	Borax Buffer
0	6.984	9.464
5	6.951	9.395
10	6.923	9.332
15	6.900	9.276
20	6:881	9.225
25	6.865	9.180
30	6.853	9.139
35	6.844	9.102
38	6.840	9.081
40	6.838	9.068
45	6.834	9.038
50	6.833	9.011

°C	Phosphate Buffer	Borax Buffer
55	6.834	8.985
60	6.836	8.962
70	6.845	8.921
80	6.859	8.885
90	6.877	8.850
95	6.886	8.833

If the electrode is far off right values for the buffers, the starting and the end point of the titration must be corrected. The new values can be calculated using the same equation as for pH correction. In table 2 the starting and end points have been calculated for few values of the pH buffer 9.22.

TABLE 2

Values of starting and end point for CO_2 titration. The pH meter is adjusted to the 6.88 buffer, and the buffer 9.22 is measured.

I. Measured value of buffer 9.22 .

II. pH at the starting of CO_2 titration.

III. pH at the end of CO_2 titration.

I	II	III	I	II	III
8.7	7.91	4.48	9.24	8.21	3.77
8.75	7.93	4.42	9.26	8.22	3.75
8.80	7.96	4.35	9.28	8.23	3.72
8.85	7.99	4.29	9.30	8.25	3.69
8.90	8.01	4.22	9.32	8.26	3.67
8.95	8.04	4.16	9.34	8.27	3.64
9.00	8.08	4.09	9.36	8.28	3.62
9.02	8.09	4.06	9.38	8.29	3.59
9.04	8.10	4.04	9.40	8.30	3.56
9.06	8.11	4.01	9.50	8.36	3.43
9.08	8.12	3.98	9.55	8.39	3.37
9.10	8.13	3.96	9.60	8.41	3.30
9.12	8.14	3.93	9.70	8.47	3.17
9.14	8.15	3.91	9.80	8.53	3.04
9.16	8.17	3.88	9.90	8.58	2.90
9.18	8.18	3.85	10.00	8.64	2.77
9.20	8.19	3.83			
9.22	8.20	3.80			

Determination of H_2S by dithizone

Hydrogen sulphide is determined by titration with $Hg(CH_3COO)_2$ solution.

Equipment and reagents necessary for the field measurement of hydrogen sulphide are:

1) 10 ml burette calibrated at 0.05 ml intervals, burette stand and clamp or 1 ml micro syringe.
2) 50 ml Erlenmayer flask.
3) 1.0 ml, 5.0 ml and 10 ml pipettes.
4) 5.0 ml or 10 ml measuring cylinder.
5) Glass rod
6) Acetone
7) 5 N NaOH solution. Dissolve 200 g NaOH in 1 liter distilled water.
8) Solid dithizone.
9) 0.001 M $Hg(CH_3COO)_2$ solution freshly prepared. Dissolve 0.3187 g $Hg(CH_3COO)_2$ in 1 liter distilled water.

Procedure:

1) Measure 5 ml 5N NaOH and 5 ml acetone into 50 ml Erlenmayer flask.
2) Add 1.0 - 10 ml of sample and distilled water to the flask. The amount of sample depends on the H_2S concentration. The total amount sample + distilled water should be 10 ml.
3) Add small grain of solid dithizone.
4) Titrate with 0.001 M $Hg(CH_3COO)_2$ to red endpoint.
5) Record volume of sample and amount of $Hg(CH_3COO)_2$ needed.
6) $$\text{ppm } H_2S = \frac{\text{ml } Hg(CH_3COO)_2 \cdot 34}{\text{ml sample}}$$

During the titration, black precipitate of HgS forms. The end point is decided when the colour changes from yellow

colour of the dithizone in alkaline solution to the red colour of the Hg-dithizonate. If the concentration of H_2S is high the sample becomes yellowish brown and even black during titration. This is caused by the HgS precipitate and makes the endpoint uncertain. In the case of high concentration of H_2S it is better to reduce the volume of the sample.

Spectrophotometric Determination of Silica

This method is based on the reaction of silica with molybdate ions at pH of 1.2 - 1.5. A green silicomolybdate complex is formed which is determined by spectrophotometry.

If the concentration of silica in thermal water is higher than 100 ppm, the silica polymerizes and if the polymerized silica will not react with molybdate in the cold. Treatment with alkali converts it all to the ionic state.

As described under sample collection it is desirable to dilute samples containing more than 100 ppm SiO_2 sufficiently to bring the final silica concentration below 100 ppm. When this is done, later analysis should follow the procedure described for samples containing less than 100 ppm SiO_2. Dilution below 100 ppm is necessary for saline waters. The silica in excess of this concentration will precipitate upon storage for one week or less.

The adopted procedure covers the concentration range of 20 - 500 ppm. Higher concentrations can be determined by taking smaller aliquot. No interference will occur from elements present in the thermal waters. Only colour or turbidity of the sample will interfere. High concentrations of hydrogen sulphide may reduce the silicomolybdate complex to molybdenum blue. This can be prevented by oxidising of the sulphide with jodine.

The main disadvantage of this method is the unstability of colour of the solution. This necessitates that samples and standards need to be prepared at the same time and that absorbance must be read between 10 and 60 minutes after developing the colour.

Average difference between duplicate samples should be 3% or less over the whole concentration range.

Procedure

Sample containing more than 100 ppm SiO_2	Samples containing less than 100 ppm SiO_2
1) Pipette 5 ml sample into platinum crucible or teflon beaker	1) Pipette 5 ml sample into 50 ml volumetric flash
1a) Add 0.5 ml of 1N NaOH solution	
1b) Add 5 ml distilled water and heat on a steam bath for 10 minutes. Take care that there is no significant loss of volume by evaporation	
1c) When cold transfer the solution to a 50 ml volumetric flask	
1d) Add 0.5 ml of 1N HCl	

If the sample contains high concentration of hydrogen sulphide follow step 2-3 otherwise go to step 4.

2) Add iodine solution dropwise until the solution in the volumetric flask becomes yellow or yellow brown
3) Destroy the yellow or yellow brown colour by adding sodium thiosulphate dropwise

4) Add 2 ml of ammonium molybdate solution
5) Add 1 ml of 6N hydrochloric acid and fill to the mark. Mix and leave for 15 minutes
6) Read the absorption at 410 millimicron within 60 minutes.

Reagents

1) Sodium hydroxide, analytical reagent grade
2) 1N sodium hydroxide (NaOH). Dissolve 40 g of the reagent in distilled water and dilute to 1 litre. This solution is required only for digesting samples containing more than 100 ppm SiO_2.
3) Hydrochloric acid, sp. gr. 1. 18 or 1.19, analytical reagent grade.
4) 1N hydrochloric acid (HCl) solution. Mix 40 ml of the concentrated acid with 400 ml of distilled water. This solution is needed to neutralize samples after digestion with NaOH - solution.
5) 6N hydrochloric acid (HCl) solution. Mix 240 ml of the concentrated acid with 200 ml of distilled water.
6) Ammonium molybdate solution, 10%. Dissolve 20 g of the reagent in water and dilute to 200 ml.
7) Potassium iodide (KI), analytical reagent grade.
8) Iodine resublimed (I_2), analytical reagent grade.
9) Iodine solution, approx. 0.1 N. Dissolve 2.5 g KI in 5 to 10 ml distilled water, add 1.77 g I_2 and dilute to 100 ml with distilled water.
10) Sodium thiosulphate, analytical reagent grade.
11) Sodium thiosulphate approx. 0.05N. Dissolve 1.2409 g of the reagent in 100 ml distilled water.
12) Standard silica solution 100 ppm. The solution can be obtained from manufacturers of chemicals. If not available, solution of this strength can be prepared as follows: Fuse 0.2 g of pure silica with 3g of sodium carbonate in a platinum crucible. Dissolve in water and make to 200 ml. Store in polythene bottle. It is convenient to standardise the solution by gravimetric analysis.

Standards

From the 1000 mg/l SiO_2 solution prepare standard solutions containing 20,50,100,150,200 ppm SiO_2. Proceed as described in stage 4 - 7 of the procedure.

Small quantities of sulphate can be determined by titration with barium perchlorate, using thorin as indicator. The titration is carried out in 80 % alcohol in the pH range 2.5 to 4.0. Before the titration the cations are removed by passing the sample through an ion exchange column. Phosphate makes the methode inaccurate but it is usually absent or in very low concentreatio in thermal waters.

Reagents.

1. Cation exchanger (Ionenaustaucher I, Merk Art.4765)
2. 2- propanol, analytical reagent grade.
3. Perchloric acid, sp.gr. 1.67, Analytical reagent grade.
4. Barium perchlorate, analytical reagent grade.
5. Absolute ethyl alcohol , analytical reagent grade.
6. Barium perchlorate, 0.005 M. Dissolve 2.0 g barium perchlorate trihydrate (1.68 g barium perchlorate water free) in 200 ml of distilled water and add 800 ml of ethyl alcohol. Adjust the pH to about 3.5 with perchloric acid. Standardize against sulphate standard.
7. Sodium sulphate, analytical reagent grade.
8. Sulphate standard, 1000 ppm SO_4. Dissolve 1.4796 g of Na_2SO_4 in 1000 ml of distilled water.
9. Thorin, analytical reagent grade.
10. Thorin, 0.2 %. Dissolve 0.2 g of the reagent in 100 ml of distilled water.

Apparatus

1. 25 ml byrette with ionic exchanger. The bottom of the byrette is stopped with glass wool (or cutton wool). About 15 ml of the ionic exchanger is placed in the byrette.
2. 10 ml byrette, subdivided at 0.02 ml for barium perchlorate.
3. Magnetic stirrer.
4. Porcelain evaporating dishes.

Procedure.

1. Fill the ionic exchange byrette with the sample and pass it through the column. Fill the byrette again and pass the sample through. Fill the byrette for the third time and let the sample pass dropwise to the 0 mark. Dispose the efluent.
2. Pass 10 ml of sample (or less amount if the concentration of SO_4 is high) dropwise through the ionic exchange column to the porcelein evoporating dish.
3. Add 40 ml propanol (ratio: sample/propanol 1/4)
4. Add 3 drops of thorin indicator.
5. Titrate with barium perchlorate using magnetic stirrer until first change from yellow to pink colour appears.
6. Calculations.

$$\text{ppm } SO_4 = \frac{\text{ml } Ba(ClO_4) \cdot N}{\text{ml sample}} \cdot 96062$$

Reference.

Fritz, J.S. and Yamamura, S.S, 1955. Rapid microtitration of sulphate. Analytical chemistry, vol. 27, no. 9, pp 1461-1464.

APPENDIX II: Basic statistical equations for two variables

These equations calculate the means and standard deviations derived from a set of ungrouped data points $\{(x_i,y_i),\ i = 1,2, \ldots, n\}$, or grouped data points $\{(x_i,y_i,f_i),\ i = 1,2, \ldots, n\}$. f_i denotes the frequency of repetition of (x_i,y_i).

Means $\quad \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad \bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$

Standard deviations $\quad S_x = \sqrt{\frac{\Sigma x_i^2 - n\bar{x}^2}{n-1}}$

$$Sy = \sqrt{\frac{\Sigma y_i^2 - n\bar{y}^2}{n-1}}$$

Note n is a positive integer and n > 1

APPENDIX III: Computer print out of WATCH3 and WATCH5

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SCIENCE INSTITUTE  UNU          THAILAND
1985-08-19  CHEM.               GEOTHERMOMETRY TEMPERATURES IN DEG.C                                    PROGRAM WATCH5
==================================================================================================================

5202101300830516000 1

QUARTZ  125.7    CHALCEDONY  102.1    NAK  195.3
SiO2    101.0    CO2    150.5    H2S    150.5    NaK    192.0    NaRb    999.9
NaLi    999.9    CaH    124.0    MgK    159.0    HF     158.0    H2SO4   112.0

5202102300830516000 2

QUARTZ  123.2    CHALCEDONY   99.4    NAK  205.8
SiO2     98.5    CO2    155.0    H2S    162.5    NaK    202.5    NaRb    999.9
NaLi    999.9    CaH    124.0    MgK    132.5    HF     164.0    H2SO4    88.0

5202103300830516000 3

QUARTZ  122.8    CHALCEDONY   99.0    NAK  220.1
SiO2     98.0    CO2    153.5    H2S    154.5    NaK    217.0    NaRb    999.9
NaLi    999.9    CaH    122.5    MgK    139.5    HF     161.0    H2SO4   109.5

5202104300830516000 4

QUARTZ  124.2    CHALCEDONY  100.4    NAK  219.7
SiO2     99.5    CO2    155.5    H2S    165.0    NaK    217.0    NaRb    999.9
NaLi    999.9    CaH    127.0    MgK    139.0    HF     165.5    H2SO4   105.0

5202105300830516000 5

QUARTZ  123.7    CHALCEDONY  100.0    NAK  226.8
SiO2     99.0    CO2    150.5    H2S    150.0    NaK    224.5    NaRb    999.9
NaLi    999.9    CaH    121.0    MgK    148.0    HF     158.0    H2SO4   113.5

5202106300830516000 6

QUARTZ  124.7    CHALCEDONY  101.0    NAK  227.8
SiO2    100.0    CO2    154.5    H2S    161.5    NaK    225.5    NaRb    999.9
NaLi    999.9    CaH    126.0    MgK    147.5    HF     163.5    H2SO4   109.5

5202206300830516000 7

QUARTZ  133.2    CHALCEDONY  109.9    NAK  225.7
SiO2    108.5    CO2    156.0    H2S    167.0    NaK    223.0    NaRb    999.9
NaLi    999.9    CaH    130.0    MgK    199.5    HF     167.5    H2SO4   103.0

5202207300830516000 8

QUARTZ  130.6    CHALCEDONY  107.2    NAK  243.2
SiO2    106.0    CO2    154.0    H2S    162.5    NaK    242.5    NaRb    999.9
NaLi    999.9    CaH    130.0    MgK    205.5    HF     165.0    H2SO4   115.5

5202304300830516000 9

QUARTZ  113.9    CHALCEDONY   89.7    NAK  218.7
SiO2     89.0    CO2    149.0    H2S    153.5    NaK    216.0    NaRb    999.9
NaLi    999.9    CaH    118.0    MgK    116.5    HF     153.0    H2SO4   112.5

5202306300830516001 0

QUARTZ  113.9    CHALCEDONY   89.7    NAK  217.3
SiO2     89.0    CO2    149.0    H2S    155.0    NaK    214.5    NaRb    999.9
NaLi    999.9    CaH    117.5    MgK     97.5    HF     154.0    H2SO4   109.5

5202309300830516001 1

QUARTZ  115.4    CHALCEDONY   91.3    NAK  230.2
SiO2     90.5    CO2    147.5    H2S    150.5    NaK    228.0    NaRb    999.9
NaLi    999.9    CaH    117.0    MgK    126.0    HF     151.5    H2SO4   110.5

5202310300830516001 2

QUARTZ  118.9    CHALCEDONY   94.9    NAK  211.9
SiO2     94.0    CO2    147.5    H2S    147.0    NaK    208.5    NaRb    999.9
NaLi    999.9    CaH    116.0    MgK    130.0    HF     153.5    H2SO4   110.0

5202311300830516001 3

QUARTZ  126.9    CHALCEDONY  103.3    NAK  226.8
SiO2    102.0    CO2    152.0    H2S    151.5    NaK    224.5    NaRb    999.9
NaLi    999.9    CaH    121.0    MgK    144.5    HF     159.5    H2SO4   112.0

5202312300830516001 4

QUARTZ  123.0    CHALCEDONY   99.2    NAK  223.2
SiO2     98.0    CO2    154.0    H2S    163.5    NaK    220.5    NaRb    999.9
NaLi    999.9    CaH    122.0    MgK    133.5    HF     162.5    H2SO4   109.0

5202313300830516001 5

QUARTZ  122.3    CHALCEDONY   98.5    NAK  220.3
SiO2     97.5    CO2    151.0    H2S    154.5    NaK    217.5    NaRb    999.9
NaLi    999.9    CaH    122.5    MgK    143.5    HF     158.0    H2SO4   113.5

5202314300830516001 6

QUARTZ  121.0    CHALCEDONY   97.2    NAK  227.9
SiO2     96.0    CO2    152.0    H2S    156.0    NaK    225.5    NaRb    999.9
NaLi    999.9    CaH    120.5    MgK    126.0    HF     159.0    H2SO4   115.0

6606101300830516000 1

QUARTZ  129.9    CHALCEDONY  106.4    NAK  199.3
SiO2    105.0    CO2    141.5    H2S    153.0    NaK    196.0    NaRb    999.9
NaLi    999.9    CaH    120.0    MgK    159.5    HF     158.0    H2SO4   106.5

6606102300830516000 2

QUARTZ  139.6    CHALCEDONY  116.6    NAK  195.5
SiO2    115.5    CO2    147.5    H2S    151.0    NaK    192.5    NaRb    999.9
NaLi    999.9    CaH    132.0    MgK    134.5    HF     174.0    H2SO4   123.0

6606103300830516000 3

QUARTZ  141.0    CHALCEDONY  118.1    NAK  206.8
SiO2    117.0    CO2    146.5    H2S    155.0    NaK    203.5    NaRb    999.9
NaLi    999.9    CaH    130.5    MgK    163.0    HF     167.5    H2SO4   113.0

6606104300830516000 4

QUARTZ  141.7    CHALCEDONY  118.8    NAK  196.4
SiO2    117.5    CO2    145.0    H2S    150.5    NaK    193.0    NaRb    999.9
NaLi    999.9    CaH    126.5    MgK     97.5    HF     166.0    H2SO4   114.0

6606105300830516000 5

QUARTZ  141.1    CHALCEDONY  118.2    NAK  203.2
SiO2    117.0    CO2    142.5    H2S    146.5    NaK    200.0    NaRb    999.9
NaLi    999.9    CaH    125.5    MgK    165.0    HF     162.0    H2SO4   113.0

6606201300830516000 6
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QUARTZ  138.9     CHALCEDONY  115.9     NAK  205.9
SiO2    114.5  CO2    143.5  H2S    148.0  NaK    202.5  NaRb   999.9
NaLi    999.9  CaH    118.0  MgK    155.5  HF     163.5  H2SO4  112.5

66062023008305160007

QUARTZ  141.2     CHALCEDONY  118.4     NAK  196.7
SiO2    117.0  CO2    156.5  H2S    167.5  NaK    193.5  NaRb   999.9
NaLi    999.9  CaH    137.0  MgK    136.5  HF     185.0  H2SO4  120.5
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54041013008101250001   WATCH6

SIHCOR > 2.0

GAS SOLUBILITY MULTIPLYING FACTOR :  0.20

QUARTZ  189.5     CHALCEDONY  160.2     NAK  172.4
ITERATIONS WHILE DECIDING 'TEMPERATURE' MORE THAN 1001
SiO2    163.0  CO2    191.0  H2S    187.5  NaK    170.0  NaRb   999.9
NaLi    999.9  CaH    178.0  MgK    106.0  HF     999.9  H2SO4  152.5

54041023008101250002   WATCH6

GAS SOLUBILITY MULTIPLYING FACTOR :  0.20

QUARTZ  176.7     CHALCEDONY  155.5     NAK  175.9
SiO2    157.5  CO2    177.0  H2S    163.5  NaK    173.5  NaRb   999.9
NaLi    999.9  CaH    164.0  MgK    108.0  HF     223.5  H2SO4  143.5

54041033008101250003   WATCH6

GAS SOLUBILITY MULTIPLYING FACTOR :  0.20

QUARTZ  176.2     CHALCEDONY  155.0     NAK  166.6
ITERATIONS WHILE DECIDING 'TEMPERATURE' MORE THAN 1001
SiO2    157.0  CO2    232.0  H2S    192.0  NaK    165.0  NaRb   999.9
NaLi    999.9  CaH    279.5  MgK    104.5  HF     999.9  H2SO4  187.5

54041043008101250004   WATCH6

GAS SOLUBILITY MULTIPLYING FACTOR :  0.20

QUARTZ  178.3     CHALCEDONY  157.2     NAK  182.9
SiO2    159.5  CO2    165.5  H2S    152.0  NaK    180.0  NaRb   999.9
NaLi    999.9  CaH    146.5  MgK    108.5  HF     200.0  H2SO4  134.5

54041053008101250005   WATCH6

GAS SOLUBILITY MULTIPLYING FACTOR :  0.20

QUARTZ  174.0     CHALCEDONY  152.6     NAK  169.1
SiO2    154.0  CO2    186.5  H2S    165.0  NaK    167.0  NaRb   999.9
NaLi    999.9  CaH    175.5  MgK    106.0  HF     261.5  H2SO4  148.5

54041063008101250006   WATCH6

GAS SOLUBILITY MULTIPLYING FACTOR :  0.20

QUARTZ  172.0     CHALCEDONY  150.5     NAK  166.5
ITERATIONS WHILE DECIDING 'TEMPERATURE' MORE THAN 1001
SiO2    152.0  CO2    201.0  H2S    174.0  NaK    164.5  NaRb   999.9
NaLi    999.9  CaH    182.5  MgK    105.0  HF     999.9  H2SO4  165.5

54041073008101250007   WATCH6

GAS SOLUBILITY MULTIPLYING FACTOR :  0.20

QUARTZ  172.7     CHALCEDONY  151.3     NAK  182.4
ITERATIONS WHILE DECIDING 'TEMPERATURE' MORE THAN 1001
SiO2    152.5  CO2    210.5  H2S    184.5  NaK    179.5  NaRb   999.9
NaLi    999.9  CaH    225.5  MgK    111.0  HF     999.9  H2SO4  168.5
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5202101J00H305160001 BAN PONG KUH,AMPHOE DOI SAKET CHANGWAT CHIANGMAI

PROGRAM WATCH2.

WATER SAMPLE (PPM)		STEAM SAMPLE			
PH/DEG.C	8.60/25.0	GAS (VOL.%)	REFERENCE TEMP.	DEGREES C	0.0 (QTZ)
SIO2	98.40	CO2			
NA	112.00	H2S	SAMPLING PRESSURE	BARS ABS.	
K	10.00	H2	DISCHARGE ENTHALPY	MJOUL/KG	
CA	3.94	O2	DISCHARGE	KG/SEC.	0.0
MG	0.030	CH4			
CO2	202.68	N2	MEASURED TEMPERATURE	DEGREES C	78.0
SO4	11.30		RESISTIVITY/TEMP.	OHMM/DEG.C	0.0/ 0.0
H2S	6.29		EH/TEMP.	MV/DEG.C	0.000/ 0.0
CL	5.70				
F	9.50	LITERS GAS PER KG			
DISS.SOLIDS	480.00	CONDENSATE/DEG.C			
AL	0.0000				
	0.0000				
FE	0.0000	CONDENSATE (PPM)			
NH3	0.0000	PH/DEG.C			
		CO2			
		H2S			
		NA			
		CONDENSATE WITH NAOH (PPM)			
		CO2			
		H2S			

	MEASURED DOWNHOLE TEMP. DEGREES C/METERS		FLUID INFLOW DEPTH (METERS)
CONDENSATE (PPM)	0.0	0.0	0.0
PH/DEG.C	0.0	0.0	0.0
CO2	0.0	0.0	0.0
H2S	0.0	0.0	0.0
NA	0.0	0.0	0.0
	0.0	0.0	0.0
	0.0	0.0	0.0
	0.0	0.0	0.0
CONDENSATE WITH NAOH (PPM)	0.0	0.0	0.0
CO2	0.0	0.0	0.0
H2S	0.0	0.0	0.0

IONIC STRENGTH = 0.00587 IONIC BALANCE : CATIONS (MOL.EQ.)0.00530354
ANIONS (MOL.EQ.)0.00583087
DIFFERENCE (%) -9.47

DEEP WATER (PPM)				DEEP STEAM (PPM)		GAS PRESSURES (BARS ABS.)	
SIO2	98.41	CO2	202.68	CO2	0.00	CO2	0.227E-01
NA	112.00	H2S	6.29	H2S	0.00	H2S	0.338E-03
K	10.00	H2	0.00	H2	0.00	H2	0.000E+00
CA	3.94	O2	0.00	O2	0.00	O2	0.000E+00
MG	0.030	CH4	0.00	CH4	0.00	CH4	0.000E+00
SO4	11.30	N2	0.00	N2	0.00	N2	0.000E+00
CL	5.70	NH3	0.00	NH3	0.00	NH3	0.000E+00
F	9.50					H2O	0.266E+01
DISS.S.	480.00					TOTAL	0.268E+01
AL	0.0000						
B	0.0000			H2O (%)	0.00		
FE	0.0000			BOILING PORTION	0.00		

ACTIVITY COEFFICIENTS IN DEEP WATER

H+	0.912	KSO4-	0.905	FE++	0.675	FECL+	0.902
OH-	0.901	F-	0.901	FE+++	0.437	AL+++	0.437
H3SIO4-	0.902	CL-	0.899	FEOH+	0.904	ALOH++	0.671
H2SIO4--	0.671	NA+	0.902	FE(OH)3-	0.904	AL(OH)2+	0.905
H2BO3-	0.898	K+	0.899	FE(OH)4--	0.669	AL(OH)4-	0.903
HCO3-	0.902	CA++	0.675	FEOH++	0.669	ALSO4+	0.903
CO3--	0.665	MG++	0.686	FE(OH)2+	0.905	AL(SO4)2-	0.903
HS-	0.901	CAHCO3+	0.906	FE(OH)4-	0.905	ALF++	0.671
S--	0.669	MGHCO3+	0.902	FESO4+	0.904	ALF2+	0.905
HSO4-	0.903	CAOH+	0.906	FECL++	0.669	ALF4-	0.903
SO4--	0.662	MGOH+	0.907	FECL2+	0.904	ALF5--	0.665
NASO4-	0.905	NH4+	0.898	FECL4-	0.902	ALF6---	0.400

CHEMICAL COMPONENTS IN DEEP WATER (PPM AND LOG MOLE)

H+ (ACT.)	0.00	-7.888	MG++	0.02	-6.023	FE(OH)3	0.00	0.000
OH-	2.03	-3.923	NACL	0.01	-6.638	FE(OH)4-	0.00	0.000
H4SIO4	138.55	-2.841	KCL	0.00	-8.349	FECL+	0.00	0.000
H3SIO4-	17.75	-3.729	NASO4-	0.27	-5.644	FECL2	0.00	0.000
H2SIO4--	0.02	-6.642	KSO4-	0.08	-6.240	FECL++	0.00	0.000
NAH3SIO4	1.12	-5.023	CASO4	0.20	-5.825	FECL2+	0.00	0.000
H3BO3	0.00	0.000	MGSO4	0.01	-6.992	FECL3	0.00	0.000
H2BO3-	0.00	0.000	CACO3	1.59	-4.798	FECL4-	0.00	0.000
H2CO3	11.31	-3.739	MGCO3	0.01	-7.220	FESO4	0.00	0.000
HCO3-	265.65	-2.361	CAHCO3+	2.65	-4.581	FESO4+	0.00	0.000
CO3--	1.63	-4.565	MGHCO3+	0.01	-7.100	AL+++	0.00	0.000
H2S	0.28	-5.089	CAOH+	0.01	-6.619	ALOH++	0.00	0.000
HS-	5.83	-3.753	MGOH+	0.00	-7.355	AL(OH)2+	0.00	0.000
S--	0.00	-11.526	NH4OH	0.00	0.000	AL(OH)3	0.00	0.000
H2SO4	0.00	-18.101	NH4+	0.00	0.000	AL(OH)4-	0.00	0.000
HSO4-	0.00	-8.556	FE++	0.00	0.000	ALSO4+	0.00	0.000
SO4--	10.87	-3.946	FE+++	0.00	0.000	AL(SO4)2-	0.00	0.000
HF	0.00	-7.108	FEOH+	0.00	0.000	ALF++	0.00	0.000
F-	9.50	-3.301	FE(OH)2	0.00	0.000	ALF2+	0.00	0.000
CL-	5.69	-3.794	FE(OH)3-	0.00	0.000	ALF3	0.00	0.000
NA+	111.72	-2.313	FE(OH)4--	0.00	0.000	ALF4-	0.00	0.000
K+	9.98	-3.393	FE(OH)++	0.00	0.000	ALF5--	0.00	0.000
CA++	2.18	-4.264	FE(OH)2+	0.00	0.000	ALF6---	0.00	0.000

IONIC STRENGTH = 0.00571 IONIC BALANCE : CATIONS (MOL.EQ.)0.00525219
ANIONS (MOL.EQ.)0.00577771
DIFFERENCE (%) -9.53

CHEMICAL GEOTHERMOMETERS DEGREES C 1000/T DEGREES KELVIN = 2.48

QUARTZ	129.5
CHALCEDONY	99.9
NAK	187.7

OXIDATION POTENTIAL (VOLTS) : EH H2S= -0.487 EH CH4= 99.999 EH H2= 99.999 EH NH3= 99.999

LOG SOLUBILITY PRODUCTS OF MINERALS IN DEEP WATER

	TEOR.	CALC.		TEOR.	CALC.		TEOR.	CALC.
ADULARIA	-16.212	99.999	ALBITE LOW	-15.565	99.999	ANALCIME	-12.522	99.999
ANHYDRITE	-6.043	-8.560	CALCITE	-9.981	-9.178	CHALCEDONY	-2.625	-2.841
MG-CHLORITE	-79.901	99.999	FLUORITE	-10.531	-11.128	GOETHITE	-3.530	99.999
LAUMONTITE	-26.000	99.999	MICROCLINE	-17.395	99.999	MAGNETITE	-27.427	99.999
CA-MONTMOR.	-79.646	99.999	K-MONTMOR.	-38.396	99.999	MG-MONTMOR.	-80.918	99.999
NA-MONTMOR.	-38.494	99.999	MUSCOVITE	-19.697	99.999	PREHNITE	-36.054	99.999
PYRRHOTITE	-85.028	99.999	PYRITE	-125.881	99.999	QUARTZ	-2.841	-2.841
WAIRAKITE	-24.124	99.999	WOLLASTONITE	9.985	8.499	ZOISITE	-35.439	99.999
EPIDOTE	-41.266	99.999	MARCASITE	-104.136	99.999			

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660610130083051600001 BAN SOP PONG,AMPHOE WIANG PA PAO CHANGWAT CHIANGRAI

PROGRAM WATCH2.

WATER SAMPLE (PPM)		STEAM SAMPLE			
PH/DEG.C	8.90/25.0	GAS (VOL.%)	REFERENCE TEMP.	DEGREES C	0.0 (0%)
SIO2	109.00	CO2			
NA	90.90	H2S	SAMPLING PRESSURE	BARS ABS.	
K	8.40	H2	DISCHARGE ENTHALPY	KJOUL/KG	
CA	3.22	O2	DISCHARGE	KG/SEC.	0.0
MG	0.020	CH4			
CO2	146.42	N2	MEASURED TEMPERATURE	DEGREES C	92.0
SO4	6.20		RESISTIVITY/TEMP.	OHMM/DEG.C	0.0/ 0.0
H2S	9.22		EH/TEMP.	MV/DEG.C	0.000/ 0.0
CL	5.90				
F	11.00	LITERS GAS PER KG			
DISS.SOLIDS	420.00	CONDENSATE/DEG.C	MEASURED DOWNHOLE TEMP. DEGREES C/METERS		FLUID INFLOW DEPTH (METERS)
AL	0.0000				
	0.0000				
FE	0.0800	CONDENSATE (PPM)	0.0	0.0	0.0
NH3	0.0000	PH/DEG.C	0.0	0.0	0.0
		CO2	0.0	0.0	0.0
		H2S	0.0	0.0	0.0
		NA	0.0	0.0	0.0
			0.0	0.0	0.0
			0.0	0.0	0.0
			0.0	0.0	0.0
		CONDENSATE WITH NAOH (PPM)	0.0	0.0	0.0
		CO2	0.0	0.0	0.0
		H2S	0.0	0.0	0.0

IONIC STRENGTH = 0.00481 IONIC BALANCE : CATIONS (MOL.EQ.)0.00430734
ANIONS (MOL.EQ.)0.00476881
DIFFERENCE (%) -10.17

DEEP WATER (PPM)				DEEP STEAM (PPM)		GAS PRESSURES (BARS ABS.)	
SIO2	109.01	CO2	146.42	CO2	0.00	CO2	0.150E-01
NA	90.90	H2S	9.22	H2S	0.00	H2S	0.435E-03
K	8.40	H2	0.00	H2	0.00	H2	0.000E+00
CA	3.22	O2	0.00	O2	0.00	O2	0.000E+00
MG	0.020	CH4	0.00	CH4	0.00	CH4	0.000E+00
SO4	6.20	N2	0.00	N2	0.00	N2	0.000E+00
CL	5.90	NH3	0.00	NH3	0.00	NH3	0.000E+00
F	11.00					H2O	0.301E+01
DISS.S.	420.00					TOTAL	0.302E+01
AL	0.0000						
B	0.0000			H2O (%)	0.00		
FE	0.0800			BOILING PORTION	0.00		

ACTIVITY COEFFICIENTS IN DEEP WATER

H+	0.918	KSO4-	0.912	FE++	0.695	FECL+	0.909
OH-	0.908	F-	0.908	FE+++	0.463	AL+++	0.463
H3SIO4-	0.909	CL-	0.907	FEOH+	0.911	ALOH++	0.692
H2SIO4--	0.692	NA+	0.909	FE(OH)3-	0.911	AL(OH)2+	0.912
H2BO3-	0.906	K+	0.907	FE(OH)4--	0.690	AL(OH)4-	0.910
HCO3-	0.909	CA++	0.695	FEOH++	0.690	ALSO4+	0.910
CO3--	0.687	MG++	0.705	FE(OH)2+	0.912	AL(SO4)2-	0.910
HS-	0.908	CAHCO3+	0.913	FE(OH)4-	0.912	ALF++	0.692
S--	0.690	MGHCO3+	0.909	FESO4+	0.911	ALF2+	0.912
HSO4-	0.910	CAOH+	0.913	FECL++	0.690	ALF4-	0.910
SO4--	0.684	MGOH+	0.914	FECL2+	0.911	ALF5--	0.687
NASO4-	0.912	NH4+	0.906	FECL4-	0.909	ALF6---	0.430

CHEMICAL COMPONENTS IN DEEP WATER (PPM AND LOG MOLE)

H+ (ACT.)	0.00	-7.966	MG++	0.02	-6.185	FE(OH)3	0.01	-7.259
OH-	2.70	-3.860	NACL	0.01	-6.684	FE(OH)4-	0.12	-6.017
H4SIO4	149.64	-2.808	KCL	0.00	-8.374	FECL+	0.00	-10.428
H3SIO4-	23.45	-3.608	NASO4-	0.13	-5.957	FECL2	0.00	-22.175
H2SIO4--	0.03	-6.451	KSO4-	0.04	-6.534	FECL++	0.00	-25.214
NAH3SIO4	1.23	-4.983	CASO4	0.11	-6.086	FECL2+	0.00	-28.435
H3BO3	0.00	0.000	MGSO4	0.01	-7.353	FECL3	0.00	-32.785
H2BO3-	0.00	0.000	CACO3	1.36	-4.868	FECL4-	0.00	-37.728
2CO3	7.33	-3.928	MGCO3	0.00	-7.411	FESO4	0.00	-9.398
HCO3-	192.49	-2.501	CAHCO3+	1.89	-4.729	FESO4+	0.00	-23.429
CO3--	1.32	-4.656	MGHCO3+	0.00	-7.373	AL+++	0.00	0.000
H2S	0.35	-4.986	CAOH+	0.02	-6.521	ALOH++	0.00	0.000
HS-	8.61	-3.585	MGOH+	0.00	-7.355	AL(OH)2+	0.00	0.000
S--	0.00	-11.251	NH4OH	0.00	0.000	AL(OH)3	0.00	0.000
H2SO4	0.00	-18.401	NH4+	0.00	0.000	AL(OH)4-	0.00	0.000
HSO4-	0.00	-8.821	FE++	0.00	-7.601	ALSO4+	0.00	0.000
SO4--	5.98	-4.206	FE+++	0.00	-24.845	AL(SO4)2-	0.00	0.000
HF	0.00	-7.077	FEOH+	0.02	-6.557	ALF++	0.00	0.000
F-	11.00	-3.237	FE(OH)2	0.01	-6.954	ALF2+	0.00	0.000
CL-	5.89	-3.779	FE(OH)3-	0.00	-8.533	ALF3	0.00	0.000
NA+	90.63	-2.404	FE(OH)4--	0.00	-12.990	ALF4-	0.00	0.000
K+	8.39	-3.669	FE(OH)++	0.00	-17.111	ALF5--	0.00	0.000
CA++	1.88	-4.328	FE(OH)2+	0.00	-11.021	ALF6---	0.00	0.000

IONIC STRENGTH = 0.00464 IONIC BALANCE : CATIONS (MOL.EQ.)0.00427143
ANIONS (MOL.EQ.)0.00473531
DIFFERENCE (%) -10.30

CHEMICAL GEOTHERMOMETERS DEGREES C 1000/T DEGREES KELVIN = 2.46

QUARTZ	133.7
CHALCEDONY	104.2
NAK	191.4

OXIDATION POTENTIAL (VOLTS) : EH H2S= -0.506 EH CH4= 99.999 EH H2= 99.999 EH NH3= 99.999

LOG SOLUBILITY PRODUCTS OF MINERALS IN DEEP WATER

	TEOR.	CALC.		TEOR.	CALC.		TEOR.	CALC.
ADULARIA	-16.090	99.999	ALBITE LOW	-15.454	99.999	ANALCIME	-12.443	99.999
ANHYDRITE	-6.107	-8.856	CALCITE	-10.064	-9.305	CHALCEDONY	-2.596	-2.808
MG-CHLORITE	-79.904	99.999	FLUORITE	-10.535	-11.044	GOETHITE	-3.359	-2.216
LAUMONTITE	-25.864	99.999	MICROCLINE	-17.249	99.999	MAGNETITE	-27.097	-19.874
CA-MONTMOR.	-78.990	99.999	K-MONTMOR.	-38.029	99.999	MG-MONTMOR.	-80.279	99.999
NA-MONTMOR.	-38.138	99.999	MUSCOVITE	-19.534	99.999	PREHNITE	-35.990	99.999
PYRRHOTITE	-82.915	-65.915	PYRITE	-122.930	-89.207	QUARTZ	-2.808	-2.808
WAIRAKITE	-24.067	99.999	WOLLASTONITE	9.876	8.638	ZOISITE	-35.414	99.999
EPIDOTE	-40.949	99.999	MARCASITE	-101.405	-89.207			

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5404101300810125000 1 pa pae hot spring amphoe mae taeng changwat chiangmai

PROGRAM WATCH3. TEMPERATURE FIXING STEAM LOSS 100.0 DEGREES C

WATER SAMPLE (PPM)		STEAM SAMPLE			
PH/DEG.C	9.50/25.0	GAS (VOL.%)	REFERENCE TEMP.	DEGREES C	0.0 (DTZ)
SIO2	272.80	CO2			
NA	82.00	H2S	SAMPLING PRESSURE	BARS ABS.	
K	5.60	H2	DISCHARGE ENTHALPY	MJOUL/KG	
CA	2.30	O2	DISCHARGE	KG/SEC.	0.0
MG	0.100	CH4			
CO2	119.70	N2	MEASURED TEMPERATURE	DEGREES C	99.0
SO4	10.00		RESISTIVITY/TEMP.	OHMM/DEG.C	0.0/ 0.0
H2S	8.80		EH/TEMP.	MV/DEG.C	0.000/ 0.0
CL	1.00				
F	11.50	LITERS GAS PER KG			
DISS.SOLIDS	425.00	CONDENSATE/DEG.C	MEASURED DOWNHOLE TEMP. DEGREES C/METERS		FLUID INFLOW DEPTH (METERS)
AL	0.0000				
	0.0000				
FE	0.0800	CONDENSATE (PPM)	0.0	0.0	0.0
NH3	0.0000	PH/DEG.C	0.0	0.0	0.0
		CO2	0.0	0.0	0.0
		H2S	0.0	0.0	0.0
		NA	0.0	0.0	0.0
			0.0	0.0	0.0
			0.0	0.0	0.0
			0.0	0.0	0.0
		CONDENSATE WITH NAOH (PPM)	0.0	0.0	0.0
		CO2	0.0	0.0	0.0
		H2S	0.0	0.0	0.0

IONIC STRENGTH = 0.00523 IONIC BALANCE : CATIONS (MOL.EQ.)0.00374986
ANIONS (MOL.EQ.)0.00557937
DIFFERENCE (%) -39.22

DEEP WATER (PPM)				DEEP STEAM (PPM)		GAS PRESSURES (BARS ABS.)	
SIO2	227.78	CO2	218.37	CO2	0.00	CO2	0.412E-01
NA	68.46	H2S	12.10	H2S	0.00	H2S	0.731E-03
K	4.68	H2	0.00	H2	0.00	H2	0.000E+00
CA	1.92	O2	0.00	O2	0.00	O2	0.000E+00
MG	0.083	CH4	0.00	CH4	0.00	CH4	0.000E+00
SO4	8.35	N2	0.00	N2	0.00	N2	0.000E+00
CL	0.83	NH3	0.00	NH3	0.00	NH3	0.000E+00
F	9.60					H2O	0.116E+02
DISS.S.	354.83					TOTAL	0.116E+02
AL	0.0000						
B	0.0000			H2O (%)	0.00		
FE	0.0668			BOILING PORTION	0.00		

GAS SOLUBILITY MULTIPLYING FACTOR : 0.20

ACTIVITY COEFFICIENTS IN DEEP WATER

H+	0.910	KSO4-	0.903	FE++	0.670	FECL+	0.901
OH-	0.900	F-	0.900	FE+++	0.428	AL+++	0.428
H3SIO4-	0.901	CL-	0.899	FEOH+	0.903	ALOH++	0.667
H2SIO4--	0.667	NA+	0.901	FE(OH)3-	0.903	AL(OH)2+	0.903
H2BO3-	0.898	K+	0.899	FE(OH)4--	0.665	AL(OH)4-	0.902
HCO3-	0.901	CA++	0.670	FEOH++	0.665	ALSO4+	0.902
CO3--	0.662	MG++	0.681	FE(OH)2+	0.903	AL(SO4)2-	0.902
HS-	0.900	CAHCO3+	0.905	FE(OH)4-	0.903	ALF++	0.667
S--	0.665	MGHCO3+	0.901	FESO4+	0.903	ALF2+	0.903
HSO4-	0.902	CAOH+	0.905	FECL++	0.665	ALF4-	0.902
SO4--	0.659	MGOH+	0.905	FECL2+	0.903	ALF5--	0.662
NASO4-	0.903	NH4+	0.898	FECL4-	0.901	ALF6---	0.396

CHEMICAL COMPONENTS IN DEEP WATER (PPM AND LOG MOLE)

H+ (ACT.)	0.00	-7.324	MG++	0.06	-5.630	FE(OH)3	0.01	-6.986
OH-	1.83	-3.969	NACL	0.00	-7.452	FE(OH)4-	0.13	-5.965
H4SIO4	350.60	-2.438	KCL	0.00	-9.125	FECL+	0.00	-12.768
H3SIO4-	13.15	-3.859	NASO4-	0.25	-5.674	FECL2	0.00	-22.218
H2SIO4--	0.00	-7.451	KSO4-	0.06	-6.339	FECL++	0.00	-25.969
NAH3SIO4	0.57	-5.317	CASO4	0.16	-5.935	FECL2+	0.00	-29.990
H3BO3	0.00	0.000	MGSO4	0.06	-6.313	FECL3	0.00	-34.993
H2BO3-	0.00	0.000	CACO3	0.36	-5.450	FECL4-	0.00	0.000
.2CO3	90.38	-2.834	MGCO3	0.00	-7.304	FESO4	0.00	-11.212
HCO3-	211.50	-2.460	CAHCO3+	2.47	-4.613	FESO4+	0.00	-23.217
CO3--	0.15	-5.589	MGHCO3+	0.02	-6.548	AL+++	0.00	0.000
H2S	2.78	-4.088	CAOH+	0.01	-6.783	ALOH++	0.00	0.000
HS-	9.04	-3.563	MGOH+	0.01	-6.565	AL(OH)2+	0.00	0.000
S--	0.00	-11.443	NH4OH	0.00	0.000	AL(OH)3	0.00	0.000
H2SO4	0.00	-15.766	NH4+	0.00	0.000	AL(OH)4-	0.00	0.000
HSO4-	0.01	-7.272	FE++	0.00	-9.572	ALSO4+	0.00	0.000
SO4--	7.94	-4.083	FE+++	0.00	-25.856	AL(SO4)2-	0.00	0.000
HF	0.02	-5.954	FEOH+	0.00	-8.375	ALF++	0.00	0.000
F-	9.58	-3.297	FE(OH)2	0.00	-8.455	ALF2+	0.00	0.000
CL-	0.83	-4.629	FE(OH)3-	0.00	-9.484	ALF3	0.00	0.000
NA+	68.30	-2.527	FE(OH)4--	0.00	-14.288	ALF4-	0.00	0.000
K+	4.66	-3.924	FE(OH)++	0.00	-17.670	ALF5--	0.00	0.000
CA++	0.75	-4.729	FE(OH)2+	0.00	-10.954	ALF6---	0.00	0.000

IONIC STRENGTH = 0.00403 IONIC BALANCE : CATIONS (MOL.EQ.)0.00315714
ANIONS (MOL.EQ.)0.00468445
DIFFERENCE (%) -38.95

CHEMICAL GEOTHERMOMETERS DEGREES C 1000/T DEGREES KELVIN = 2.18

QUARTZ	186.5
CHALCEDONY	159.0
NAK	161.9

OXIDATION POTENTIAL (VOLTS) : EH H2S= -0.542 EH CH4= 99.999 EH H2= 99.999 EH NH3= 99.999

LOG SOLUBILITY PRODUCTS OF MINERALS IN DEEP WATER

	TEOR.	CALC.		TEOR.	CALC.		TEOR.	CALC.
ADULARIA	-14.960	99.999	ALBITE LOW	-14.435	99.999	ANALCIME	-11.746	99.999
ANHYDRITE	-6.972	-9.167	CALCITE	-11.206	-10.671	CHALCEDONY	-2.286	-2.438
MG-CHLORITE	-81.072	99.999	FLUORITE	-10.666	-11.590	GOETHITE	-1.012	-1.994
LAUMONTITE	-24.736	99.999	MICROCLINE	-15.853	99.999	MAGNETITE	-22.743	-21.763
CA-MONTMOR.	-73.920	99.999	K-MONTMOR.	-35.058	99.999	MG-MONTMOR.	-75.352	99.999
NA-MONTMOR.	-35.271	99.999	MUSCOVITE	-18.231	99.999	PREHNITE	-35.918	99.999
PYRRHOTITE	-55.708	-56.512	PYRITE	-86.125	-73.509	QUARTZ	-2.413	-2.438
WAIRAKITE	-23.832	99.999	WOLLASTONITE	8.660	7.307	ZOISITE	-35.850	99.999
EPIDOTE	-37.756	99.999	MARCASITE	-67.042	-73.509			

APPENDIX IV: Chemical geothermometers

Recommended equations for chemical geothermometers

		Range (°C)	Source
Chalcedony			
(1)	$t°C = \frac{1112}{4.91 - \log SiO_2} - 273.15$	25 – 180	(1)
(2)*	$t°C = \frac{1264}{5.31 - \log SiO_2} - 273.15$	100 – 180	(1)
Quartz			
(3)	$t°C = \frac{1309}{5.19 - \log SiO_2} - 273.15$	0 – 250	(2)
(4)	$t°C = \frac{1164}{4.90 - \log SiO_2} - 273.15$	180 – 300	(1)
(5)*	$t°C = \frac{1522}{5.75 - \log SiO_2} - 273.15$	100 – 250	(2)
(6)*	$t°C = \frac{1498}{5.70 - \log SiO_2} - 273.15$	180 – 300	(1)
Na – K (low albite/K – feldspar)			
(7)	$t°C = \frac{933}{0.993 + \log Na/K} - 273.15$	25 – 250	(1)
(8)	$t°C = \frac{1319}{1.699 + \log Na/K} - 273.15$	250 – 350	(1)
Na – K – Ca			
(9)	$t°C = \frac{1647}{2.24 + \log Na/K + \beta \dagger \log\sqrt{Ca/Na}} - 273.15$	4 – 340	(3)
Na – Li			
(10)‡	$t°C = \frac{1000}{\log Na/Li - 0.14} - 273.15$	20 – 340	(4)
(11)§	$t°C = \frac{1195}{\log Na/Li - 0.39} - 273.15$	20 – 340	(4)

Concentrations are in ppm except for the Na – K – Ca geothermometer where they are in mols/l.

*After adiabatic steam loss to 100°C.

†$\beta = 4/3$ for $\sqrt{Ca/Na} > 1$ and $t < 100°C$; $\beta = 1/3$ for $\sqrt{Ca/Na} < 1$ or $t_{A\beta} > 100°C$.

‡ For waters of low to moderate salinity.

§For marine waters and brines. It may be that the latter Na – Li equation is also appropriate for waters in basaltic rocks.

(1) Arnórsson *et al.* (1983b); (2) Fournier (1977); (3) Fournier and Truesdell (1973); and (4) Fouillac and Michard (1981).