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# A STUDY OF WATER-ROCK EQUILIBRIUM OF LOW TEMPERATURE GEOTHERMAL RESERVOIRS IN CHINA

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## ABSTRACT

Ten typical water samples with a range of temperature 13-90 °C were collected from cold spring and warm springs located in lower mountain and plain areas, and from geothermal wells located in different geological setting in plain area represent all types of geothermal reservoirs in the North China and the East China. According to their detailed chemical composition, water-rock equilibrium computation and other geochemical methods were used to research their hydrogeochemical characteristics. The results indicate different geological origins and developing potential for these geothermal reservoirs.

## 1. INTRODUCTION

The vast main land of China is far from the Pacific Rim Geothermal Zone and the Mediterranean-Himalayan Geothermal Zone. Most of hot springs and geothermal wells in China located within inner Euro-Asian Plate. They are low temperature geothermal resources mostly. But there are different geological settings and various types of origin for them. However such low temperature geothermal resources in developed Eastern China is significant, especially in Beijing, Tianjin and the North China areas. Local geothermal resources have been utilized in space heating, medical treatment, industrial processing, agricultural greenhouse, amusement center and holiday resort. Present development has gained obvious economic and social benefit. Fitting in with the need of the development from many of these geothermal fields the research and forecast of potential geothermal resources have been undertaken in various aspects. Geochemical research is one of these components (Zheng *et al*., 1997).

Nine geothermal water samples were collected from five geological units (Table 1 and Fig.1). As a comparison, collected a typical cold spring sample.

## 2. GEOLOGICAL TYPES OF LOW TEMPERATURE GEOTHERMAL RESERVOIR IN CHINA

Low temperature geothermal resources of Eastern China occurred in different geological background. Huang (1993) divided the hot springs of China into three types. There is no magmatic activity type for low temperature geothermal reservoir in Eastern China. Hot springs in this study belong to uplifted fault type, while geothermal wells belong to subsided basin type. They are typical representatives of low temperature geothermal reservoirs in China. Author divided these low temperature geothermal reservoirs into five geological subtypes in order to show their detailed geological difference.

### 2.1 Hot Spring of Fold Mountain

Hot springs occurred in mid-low mountain areas in the North China and the East China belong to this type. There is only very thin Quaternary coverage in such hot spring area. Geothermal water raises up from neotectonic faults and fractures of basement rocks to occur as springs. Chicheng Tangshan Warm Spring (sample No.2) and Houhaoyao Hot Spring (sample No.3) occurred in Proterozoic siliceous rock and Archaeozoic gneiss respectively.

### 2.2 Hot Spring of Mountain Margin

This type of hot spring occurs at margin of lower hilly area. The origin of hot spring is concerned with a contact zone between the mass of igneous rock and surrounding rock. Oxidation of polymetallic sulfide deposit in skarn zone produced thermogenesis and accumulated heat. Thermal water raises up from tectonic faults or fractures of basement rock. It formed hot spring in very limited area around the thermal passageway. There is only about 0.1 $km^2$ of area for Nanjing Tangshan Warm Spring.

### 2.3 Geothermal Water in Shallow Buried Graben

There are a few relatively shallow buried grabens in margin area of tectonic down-warping region. Groundwater passed through deep circulation to become thermal water and reserved in permeable foundation bed of the graben. The overlying impermeable formation formed its cap rock for temperature-maintenance. Beijing Urban Geothermal Field is a typical example of this type of geothermal reservoir. Thermal water reserved in Proterozoic siliceous dolomite in 700–2,000 m depth. Fundamental fault formed passageway for deep thermal water raising. The relative fundamental uplift formed geothermal enrichment area.

### 2.4 Geothermal Water in Cap Rock of Deep Tectonic Basin

Tertiary very-thick clastic rock covered many deep buried uplifts and depressions in tectonic down-warping region. Geothermal water reserved in permeable sandstone formation in about one thousand some meters depth. Mudstone formed relative aquifuge and cap rock for temperature-maintenance. This type of geothermal reservoir distributed widely in Tianjin and the North China areas.

### 2.5 Geothermal Water in Deep Tectonic Basin

There are many deep buried uplifts and depressions in tectonic down-warping region. They were buried in 2,000–5,000 m depths. Uplift, or say ancient hidden mountain, occupied relative favorable condition. Deep thermal water floated and moved up to the permeable formation. They reserved in Palaeozoic or Preterozoic carbonate reservoirs. The overlying Cenozoic impermeable or permeable formations formed their cap rock for temperature-maintenance. There are very large areas for this type of reservoir. And regional deep faults linked up the deeper heat source.

## 3. HYDROGEOCHEMICAL FEATURES OF LOW TEMPERATURE GEOTHERMAL RESERVOIR

There are various water chemical types for five types of low temperature geothermal reservoirs and mountain area cold spring. They occupy a certain space position respectively in Lengelier-Ludwig Diagram (Fig.2). It means that there are different origins for them. We may just say that samples No.5 & 6 might be a mixture between thermal water (sample No.9 & 10) and cold spring.

### 3.1 Cold Spring

Cold spring is typical shallow-circulation groundwater. It is $CaMg\text{-}HCO_3$ water type with low total dissolved solids about 0.2-0.3 g/l. Giggenbach (1986) deduced K-Mg Geothermometer from thermodynamic equilibrium. It was called drilling touchable temperature. It shows the temperature reached in its groundwater circulation. The Emperor's Spring has a temperature of 13°C. Its $T_{km}$ (K-Mg geothemometer) showed 17.1°C. Quartz geothermometer showed the quartz temperature in 51.1-52.4°C.

### 3.2 Hot Spring of Fold Mountain

Its water chemical type is $Na\text{-}SO_4$. Although dominated Na in cation represents geothermal origin. But its dominated anion is neither $HCO_3$ of typical cold water nor Cl of typical geothermal water. There is medium the total dissolved solids about 0.8-1.0 g/l. Sampled two springs are 65°C & 83°C in temperature. Their $T_{km}$ temperature is 80.2°C and 125.4°C respectively. The quartz temperature is 113.9-117.0°C.

### 3.3 Hot Spring of Mountain Margin

There is special water chemical type of $Ca\text{-}SO_4$ for this type of hot spring. Although $SO_4$ as anion represents a certain of geothermal origin, but Ca as cation is typical cold water type usually. There is mid-high of TDS about 1.2 g/l. The Nanjing Tangshan Warm Spring is 61°C in temperature. Its $T_{km}$ temperature is 67.1°C. Quartz temperature is 101.6-102.2°C.

### 3.4 Geothermal Water in Shallow Buried Graben

This type of geothermal water is $Na\text{-}HCO_3\text{-}SO_4$ or $Na\text{-}Ca\text{-}HCO_3\text{-}SO_4$ water type. The Na and $SO_4$ of them represent geothermal origin. But Ca and $HCO_3$ represent cold water origin. So it shows obviously that they are mixture of deep circulation of thermal water and shallow circulation of cold ground water. There are mid-low TDS about 0.5-0.7 g/l. Water temperature is 56-61°C. Their $T_{km}$ temperature are 65.1-74.2°C. Quartz temperature is 83.9-85.4°C.

### 3.5 Geothermal Water in Cap Rock of Deep Tectonic Basin

This Geothermal Water is $Na\text{-}Cl\text{-}HCO_3$ or $Na\text{-}Cl\text{-}HCO_3\text{-}SO_4$ type. The Na and Cl of them represent typical geothermal origin. But $HCO_3$ is the composition of typical cold groundwater. So it represented a mixture of thermal water from deep section and cold water from local. Its TDS is mid-high about 1.0-1.3 g/l. Thermal water occurred in 39-46°C. Their $T_{km}$ temperature are 53.6-60.1°C. Quartz temperature is 64.2-88.5°C.

### 3.6 Geothermal Water in Deep Tectonic Basin

It has typical Na-Cl water type as typical high-temperature geothermal field in the world. There is high TDS about 1.9-3.8 g/l. Thermal water is in 82-90°C temperature. Their $T_{km}$ temperature are as high as 120.2°C and 144.5°C. Quartz temperature is 111.8-148.9°C.

## 4. CHARACTERISTICS OF WATER-ROCK EQUILIBRIUM

Ten water samples were computed using the WATCH3 water-rock equilibrium program, which was compiled by Icelandic scientists (Arnorsson *et al*, 1982; Arnorsson *et al*, 1983), according to their chemical composition and selected temperature (10-90°C with interval of 10°C). WATCH3 computes the relationship between the chemistry of the deep circulation water and solubility of minerals to predict particular mineral-solution equilibrium. Its computation consists of the following steps:

- Ionic strength and ionic balance calculated according to the analyzed chemical composition of water sampled at the spring or well head;
- Calculating the corresponding concentration of each composition in the deep water;
- Determining the activity coefficients of every species present in the deep water;
- Knowing the chemical components in the deep water;
- Ionic strength and ionic balance in deep water;
- Compute the standard chemical geothermometers;
- Finally, it shows the logarithm of the solubility products of 26 geothermal minerals in the deep water. If the calculated value is larger than its theoretical value this means that the deep water has reached saturation with this mineral. Then the presence of the mineral represents its own hydrogeochemical significance.

### 4.1 Absolute Difference between Cold Water and Thermal Water

There is absolute difference for Water-rock equilibrium between cold water and thermal water. All such minerals related to higher temperature were never occurred in cold water. For example, montmorillonites and zeolite minerals represent higher temperature environment. They present in thermal water only. The minerals related to good permeability such as adularia and albite present also in thermal water only.

### 4.2 General Intensity of Geothermal Activity (GIGA)

In computed 26 equilibrium minerals, 14 of them are related to higher temperature; 2 of them are related to good permeability. So it means that most of minerals represent further stronger geothermal activity. Therefore the total number of mineral present can basically represent the general intensity of geothermal activity. Due to 6 samples didn't analyse their hydrogen sulfide, it made 6 ferromagnesian minerals were not able to present. Hence we use the rest 20 minerals unifiedly to compare each other. The total member of mineral present is lowest in cold water, but different in thermal water (Table 2). Hot springs in fold mountain or at mountain margin represented higher or very high GIGA. In three types of geothermal reservoirs, there is lower GIGA in cap rock type of deep tectonic basin. The GIGA is in middle position for shallow buried graben type. But there is higher GIGA for deep tectonic basin.

### 4.3 Temperature Features of Geothermal Reservoir

Montmorillonite temperature
Ca-montmorillonite, Na-montmorillonite, K-montmorillonite and Mg-montmorillonite all originated in 140-150°C temperature environment. So the present of montmorillonite represents that the reservoir experienced an environment in 140-150°C temperature. According to the total number of montmorillonite present (Table 2), its alignment from high to low is VI-II & III-IV-V-I.

Zeolite temperature
Zeolite minerals are temperature-indicators too. Laumontite originates in a temperature range of 110-230°C. Wairakite originates in a range of 230-300°C. Laumontite presented in all thermal waters. Its alignment is III-II-VI-IV-V. Wairakite presented only in III and II. It is more in III than in II.

Mg-chlorite and epidote temperature
Mg-chlorite originates in a temperature range of 150-250°C. Epidote originates in a range of 250-300°C. Mg-Chlorite presented twice in III and VI each. Unfortunately we have no data for epidote in III, V and VI. It presented 9 times in II and once in IV.

Na-K geothermometer
When microline and albite both minerals are present this represents a replacement reaction between potassium (in microline) and sodium (in albite). For this case a Na-K temperature will be available. All 5 types of thermal water accorded with this condition. Their alignment is VI-III-II-IV-V.

Silica geothermometer
Quartz and chalcedony are all positive function of temperature. It indicates that geothermal water reached a certain temperature during its deep circulation so it dissolved silica, to preserve its thermal "memory". Quartz is present in all samples. This means that all these samples have reached equilibrium with quartz. It also means that the quartz geothermometer is available in this case. It's alignment is II & VI-III-IV-V-I. Chalcedony has the same case.

### 4.4 Permeability Features of Geothermal Reservoir

Pyrrhotite implies a poor permeability condition, though albite implicates a medium permeability and adularia represents a good permeability. Adularia presented in all thermal water. Its alignment is III & VI-II-IV-V. Albite has a similar case. Pyrrhotite is restricted in 4 samples with hydrogen sulfide data. It is more supersaturated in cold water. It means the deep hydrogeological condition is rather poor permeability for cold spring.

### 4.5 Granite intrusive

The present of fluorite represents an environment related to granite intrusive in the range of geothermal reservoir. Fluorite presented in II, III, IV and VI types of reservoir. It absents in cap rock reservoir. This means granite intrusive is related with pre-Tertiary formation. There is no new intrusive in studied area.

### 4.6 Acidic Sulfate Water Environment

There is a small part of geothermal reservoir in the world with acidic sulfate water environment. Anhydrite represents such a condition. Anhydrite presented only in type III of reservoir. It shows that the Nanjing Tanshan Warm Spring is another type of geothermal source, which different with all rests. It belongs to acidic sulfate water environment. It is really rather different for the water-rock equilibrium. It presented Mg-chlorite, wairakile and prehnite, which all presented occasionally in the rests of geothermal reservoirs. And zoisite presented only in this sample. All these showed that Nanjing Tangshan reservoir is related with sharn ore. Oxidation of polymetallic sulfide deposit became sulfate and produced thermogenesis. The heat accumulated in a local sealed environment. Thermal water raised up from fault and formed the warm spring.

### 4.7 Present of Calcite

Calcite is a typical representative of low temperature geothermal reservoir. It absents in all high temperature geothermal field in the world. Calcite presented more or less in all low temperature geothermal reservoirs in China (and in cold spring). The only absence is in Houhaoyao hot spring. It indicated that all geothermal reservoirs in Eastern China are low temperature type. There is no relationship with high temperature geothermal resources.

## 5. ESTIMATION OF DEVELOPMENT POTENTIAL OF LOW TEMPERATURE GEOTHERMAL RESERVOIR

Based on above water-rock equilibrium features, referring to corresponding hydrogeochemical and geological conditions, the estimation of development potential of low temperature geothermal reservoirs in China showed as following:

### 5.1 Deep Tectonic Basin Reservoir Owns Relatively Maximum Development Potential

Water-rock equilibrium expresses the general intensity of geothermal activity and the features related to high-temperature and good permeability. Deep tectonic basin reservoir dominated all of these characteristics. Its $T_{km}$ temperature indicated 120.2-144.5°C of medium temperature geothermal potential. This type of tectonic basin has huge area, e.g. several thousand square kilometers. Regional faults linked up deep heat source. So it occupys a dominant position in both aspects: quality and quantity for geothermal resources in Eastern China. There is only a shortcoming that the reservoir located in relative deeper depth. Geothermal well needs drill 2,000-3,000 m or more. It increased the developing cost.

### 5.2 Hot Springs of Fold Mountain Own Also Rather Good Development Potential

The GIGA and those features expressed by water-rock equilibrium is second only to the above. Its $T_{km}$ temperature indicated a medium temperature potential too. It is just to say that its geological scale is rather smaller than the above. The geothermal resources in Houhaoyao hot spring area (Sample No.3) was developed as an attempt. Low temperature double-medium geothermal power plant with 200 kw capacity was run for several years. And also there is direct use of the geothermal water in many aspects.

### 5.3 Shallow Buried Graben Reservoir Owns Medium Potential for Development

The GIGA and those features expressed by water-rock equilibrium in this type of reservoir located in medium position. Its geological scale is in medium-size too. It may reach hundreds square kilometers. Its reservoir depth is relatively shallower, usually in a thousand meters up or down. So its developing cost is lower. Especially in the capital Beijing area, it owns higher economic value.

### 5.4 Cap Rock Reservoir Owns Lower Potential for Development

All those dominant condition expressed by water-rock equilibrium is located at the end for this type of reservoir. Although its geological scale is large, but its geothermal resources are just “flow” without “source”. Its development can get a certain gaining in the developed economic area in Eastern China.

### 5.5 Geothermal Resources at Mountain Margin Can Be Developed in Small Scale

Although it is among the best for those dominant conditions, but by comprehensive evaluation, it has partial priority only. The geological condition is not in regional scale, but belongs to a local specialized environment. So its dominance is in quality, but not in quantity. Its resources quantity may be less. So it can be developed in local small scale.

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Table 1. Sampling location and their geological type

| Type | No | Sampling location | Geological type |
|---|---|---|---|
| I | 1 | Emperor’s Spring in Zhuolu county, Hebei province | Mountain area |
| II | 2 | Tangshan warm spring in Chicheng county, Hebei province | Fold mountain area |
| | 3 | Houhaoyao hot spring in Huailei county, Hebei province | |
| III | 4 | Tangshan warm spring in Nanjing, Jiangsu province | Mountain margin |
| IV | 5 | Geothermal well No.16 in Beijing Urban Geothermal Field | Shallow buried graben |
| | 6 | Geothermal well No.8 in Beijing Urban Geothermal Field | |
| V | 7 | Geothermal well in Transportation Division, Dagang Oil Field, Tianjin | Cap rock of deep tectonic basin |
| | 8 | Gerthermal well No.2 in Power-water Division, Renqiu Oil Field, Hebei | |
| VI | 9 | Geothermal well No.212 in Renqiu Oil Field, Hebei province | Deep tectonic basin |
| | 10 | Geothermal well in Wanjiamatou, Tianjin Wanlangzhuang Geothermal Field | |

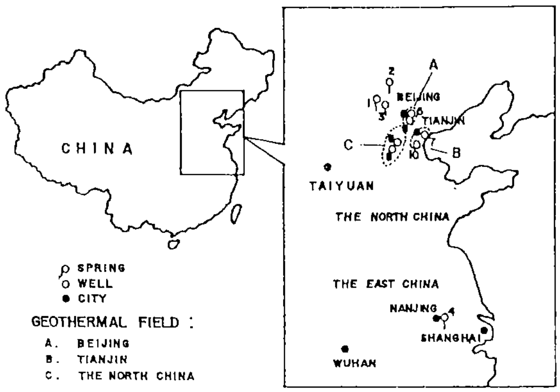


Figure 1. Location Map Showing Sampling Points

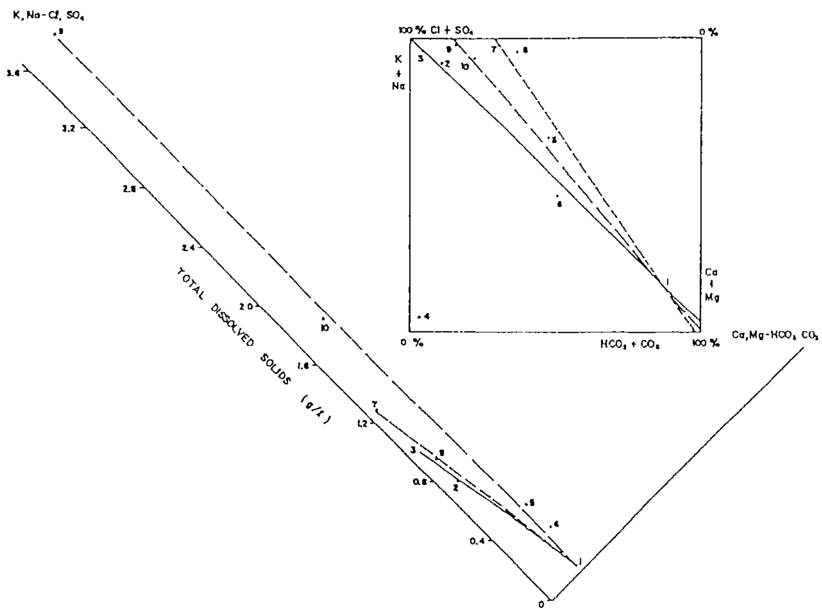


Figure 2. Langelier-Ludwig Diagram Showing Water Chemical Types of Various Waters

Table 2. Comparison of Presence Number of Equilibrium Minerals

| Type | No. | Presence number for 26 minerals | Presence number for 20 minerals | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mont. | Zeo-lite | Chlo-rite | Micro./ Albite | Quartz /chalc. | Total | Ave. in type | GIGA |
| I | 1 | 63 | 0 | 0 | 0 | 0 / 1 | 5 / 2 | 18 | 18 | -- |
| II | 2 | (76)* | 15 | 5 | 0 | 6 / 7 | 9 / 9 | 76 | 84 | Better potential |
| | 3 | 145 | 19 | 8 | 0 | 7 / 9 | 9 / 8 | 91 | | |
| III | 4 | (141)* | 34 | 15 | 2 | 6 / 9 | 9 / 7 | 141 | 141 | Local develop |
| IV | 5 | 110 | 15 | 4 | 0 | 3 / 6 | 8 / 5 | 68 | 67 | Good potential |
| | 6 | 110 | 14 | 4 | 0 | 3 / 6 | 8 / 5 | 66 | | |
| V | 7 | (46)* | 6 | 2 | 0 | 4 / 4 | 8 / 6 | 46 | 40 | Less potential |
| | 8 | (34)* | 3 | 1 | 0 | 3 / 3 | 6 / 4 | 34 | | |
| VI | 9 | (88)* | 16 | 6 | 2 | 8 / 9 | 9 / 9 | 88 | 86 | Best potential |
| | 10 | (83)* | 18 | 4 | 0 | 6 / 8 | 9 /8 | 83 | | |

* Absence of 6 ferromagnesian minerals due to no $H_2S$ data
GIGA – General Intensity of Geothermal Activity