Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

ENVIRONMENTAL IMPRINTS ON THE TEMPORAL CHANGES OF THE CHEMISTRY OF GEOTHERMAL WATER FROM SOME LOW-TEMPERATURE GEOTHERMAL FIELDS IN THE NORTH CHINA PLAIN

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Keywords: low-temperature reservoir, temporal change of chemistry, indicator of over production, North China, sustainability

ABSTRACT

The North China Plain, located to the north of the Yellow River, is a great sedimentary basin with extensive accumulation of Tertiary and Quaternary deposits, that region contains more than 30 low-temperature geothermal sites. The total areas of all discovered thermal anomalies are about 7,000 km^2. Only a few sites have been exploited such as in Beijing, Xiaotangshan, Tianjin, Tanggu, Xiongxian, Shenzhou, etc.. Depths of the geothermal wells range from 500 m to 2,000 m, and the wellhead water temperatures vary from 45℃ to 75℃.

The chemical composition and temporal changes of the low-temperature water in the North China Plain are affected by the annual climatic environment, the artificial environment, and the paleoclimatic environment. In Tanggu areas, the temporal changes in extraction amount of hot water, the rate of land subsidence and the fluoride contents, show a strong correlation with each other. In Xiaotangshan areas, the chemical composition of hot waters also show relation with the extraction amount. The chemical composition of hot water in Tanggu areas is positively related to the annual precipitation amount. In Xiaotangshan areas, the chemistry changes with a lag behind that of precipitation of about 4 months. Based on the ^{14}C and oxygen isotopic data from hot water in North China Plain, a curve has been completed showing the paleoclimatic dry-cold or wet-warm changes since last glacial period.
Understanding the effect of the regional environment on the chemistry of geothermal water would certainly be a great help to establish the models of geothermal field and of manage it properly for sustainable development.

1. INTRODUCTION

The term *environment* as used here refers to both the natural environment and an artificial environment. The former is based on the concept of natural history and formed in the evolution process of the earth. The later is based on the concept of mankind's disturbance to the natural state. The discussion is based on chemical data from two typical geothermal fields in the North China, and environmental impacts to these fields.

Land subsidence, caused by the overexploitation of geothermal water, has occurred in many geothermal fields. Geophysical methods such as microgravity, leveling, etc. were used to monitor the mass change below ground. An investigation in the Tanggu reservoir indicates that the compressed layers release the pore water into the adjacent geothermal reservoir during the course of subsidence, which causes the change of chemistry in the geothermal water. We suggest that a chemical approach can be used to monitor the land subsidence caused by overexploitatiton.

It is well known that the low-temperature geothermal fields in a great sedimentary basin are recharged by local precipitation. This conclusion is usually deduced by comparing the stable isotopes of geothermal water with that of local meteoric water. However, the recharge area and the recharge time demonstrated by that method can be ambiguous. The effect of precipitation can be reflected by the common chemical composition besides stable isotope contents in geothermal water, and moreover, it can be defined temporally and spatially. The argument is presented that the monthly chemistry change in low-temperature geothermal water (in Xiaotangshan) is affected by intro-annual distribution of precipitation, and the yearly chemistry change is affected by inter-annual distribution of precipitation (in Tanggu). The chemistry changes with short-fluctuation such as season or year, as well as with long-fluctuation occurred in hundreds and in thousands years.

Low-temperature geothermal water can be regarded as a "mixing average sample" for precipitation during a certain period. The isotopic contents of hydrogen and oxygen in precipitation are controlled by the cloud-bottom temperature, latitude, altitude, season, precipitation, and continentality. For the North China Plain, which is a relatively small geography unit, the effects of latitude, altitude, season and continentality can be regarded as approximately homogenous. Therefore, the isotopic differences of oxygen in low-temperature geothermal water from place to place might be caused by the variation of temperature and of precipitation there during a certain period. The paleoclimate changes of cold -warm or dry-wet at the North China area since the last glacial period have been revealed by measuring the isotopes of oxygen and carbon in low-temperature geothermal water.

P. M. Wright (1995) put forward a question "How can we better quantify the production capacity of a hydrothermal reservoir at an early stage in a project and thereby avoid over-development?" in his paper on the sustainable development of geothermal energy. We have given account of that on a quarter of century, a year, and a month scales, the certain chemical components of geothermal water change correspondingly with the increased exploiting, and these indicate that there is the forewarning information of overexploitation in the chemical regime of geothermal water.

2. GEOLOGICAL SETTING OF LOW-TEMPERATURE GEOTHERMAL SITES

The North China Plain, lying to the north of the Yellow River, is a great sedimentary basin filled with extensive Tertiary and Quaternary deposits (Figure 1). Lower Tertiary units are composed of argillite, sandy mudstone, fine sandstone etc., and its maximum of thickness at different areas ranges from 4,000 m to 6,000 m. Upper Tertiary units are composed of mudstone, sandstone, gravel-bearing sandy stone and sandy conglomerate, with maximum of thickness from 1,000 m to 2,900 m. Quaternary units are mainly poorly-cemented detrital sediment (clastic sediment), up to 500 m － 900 m thick. The basin basement consists mainly of limestone and dolomite of Paleozoic and Middle and Upper Proterozoic age. Indications of oil and gas have been found in Tertiary System. Eruptions of basic magma occurred in Tertiary and in Quaternary times, with the last event in Upper Pleistocene.

In the North China Plain, the average heat flow is 62±13 mW/m^2. On the basis of geothermal gradients exceeding 3.5 ℃ per 100 m with depth as defining a geothermal anomaly, there are over 30 geothermal anomalies. The anomalous areas cover about 7,000 km^2 and the average heat flow is of 65 mW/m^2. Simulation studies (Hochstein, 1985; Yao, 1993) indicate that the anomalies are due to background heat-flow being redistribution at shallow levels. The heat redistribution can be performed in two ways. One is heat conductivity. At the depth of the North China Basin, a series of small secondary grabens and horsts have formed due to uplift or subsidence of the Paleozoic and Proterozoic rocks with significant folding. The small grabens are filled with Cenozoic deposits for which heat conductivity is relatively low. Both sides of the grabens consist of bedrock with high heat-conductivity. The significant difference in heat conductivity redistributes the heat flow from depth at the center and at the both sides, thus the temperature contours rise at the centers of the grabens. The other heat redistribution method is convection-heat-transfer by groundwater flow. Groundwater flows laterally from the recharge area to the drainage area, and carries geoheat from deep parts of the grabens to shallow parts on the flank. As a result of the superimposition of these two heat-transfer actions, the geothermal anomaly occurs shallow depths.

Of more than 30 geothermal anomaly sites, only a few such as Beijing, Xiaotangshan, Tianjin, Tanggu, Xiongxian, and Shenzhou, etc. have been developed. The reservoir is mainly carbonate rocks of Paleozoic, Proterozoic time, or clastic rocks of Tertiary age which are fragmented by active faults. The depths of the geothermal wells usually varies from 500 m to 2,000 m with a maximum of more than 3,000 m. The wellhead temperature usually varies from 45℃ to 75 ℃, and the TDS in the geothermal waters ranges from 0.5 g/l to 2.0 g/l.

3. THE EFFECT OF LAND SUBSIDENCE (OVEREXPLOITATION) ON CHEMICAL REGIME OF GEOTHERMAL WATER

The Tanggu geothermal reservoir is mainly confined to the Guantao group of Upper Tertiary, which is affected by the Haihe fault. Since 1985, 26 production wells with a depth of about 2,000 m have been drilled. The geothermal water is mainly used for space heating. The heating area is 860,000 m^2. The annual total extraction amounts to 3,500,000 － 4,000,000 m^3. A water level drop of up to 70 m has been observed during periods of high production.

There are various answers for questions, such as “ does the land subsidence at Tanggu relate to the geothermal exploitation?” and “ will more serious land subsidence occur if the geothermal water is exploited continuously at the present intensity?" One possibility is that the land subsidence developed before the geothermal water was exploited on a large scale, a second possibility is that the subsidence has been mainly caused by overexploiting of cold groundwater (Figure 2). According to the data now available, there is no indications that increase of the exploitation in the future will cause the more serious land subsidence. The solid line in Figure 2 can be divided into three fractions: 1) Before 1985, the slope is very steep, which indicates rapid subsidence before the regulations for restricting the groundwater exploitation were issued by Tianjin City local government in 1985, 2) From 1986 to 1988 (a-b segment on the slid curve), curve slopes gently, due to the decrease of groundwater exploitation from 33,860,000 m^3/a in 1985 to 11,100,000 m^3/a in 1989, 3) After 1988, the slope becomes steeper again, which is undoubtedly caused by the exploitation of geothermal water on a larger scale. Since the first deep well was drilled for space heating in 1987, another 18 deep wells were drilled between 1988 and 1996. According to the trend of a-b segment of the solid curve, a dot line is drawn as the boundary line between subsidence caused by groundwater exploitation and by geothermal water exploitation. Obviously, the portion of land subsidence caused by geothermal production can not be ignored in the total land subsidence.

Monitoring data indicate that there is a positive correlation between land subsidence and fluoride contents in the geothermal water (Figure 3). The distributions of maximum fluoride contents and of maximum land subsidence at surface locations are coincident. These data could be interpreted as: 1) A considerable amount fluoride in geothermal water might originate from the “ released water” of strata compressing, 2) Fluoride contents in “released water” are greatly more than that in the “ normal recharge runoff” in the geothermal system, 3) Fluoride concentration in geothermal water in production well is resultant of fluoride from “released water” and from “normal recharge runoff”.

It is difficult to determine the fluoride concentration in “released water”. However, by means of the following technique, the fluoride contribution of “released water” to geothermal water can be calculated. Then a fraction of released water in hot water produced can be further estimated. Figure 3 shows that: 1) Since 1990 annual increment of land subsidence increased with the annual increment of production, and culminated in 1992, then, it decreased with time till the other peak occurred in 1994, but its increment was less than that in 1992, 2) The annual increment of fluoride in geothermal water decreased with time since 1990, almost to zero in 1992. A peak also appeared in 1994, but the amount was less than that in 1990-1991 period.

This history can be interpreted in the Following manner. During 1990-1995, the process of land subsidence appeared as two compressing stages. During the first stage (1990-1993), the strata were consolidated gradually. After a corresponding maximum value was reached, land subsidence was still in progress and the lithographic structure was adjusted. In 1993, the annual delta subsidence was almost zero. The second stage began in 1994, the layers adapted to a new stress condition after lithographic structure had been adjusted. The temporal changes of fluoride content are in synchronism with two stages of compression. From 1990 to 1992, the strata compression rate gradually reached a maximum, while the incremental increase of fluoride decreased gradually close to zero. This process could be analogized as a "juice extracting effect". The zero-increment of fluoride means that all the "juice " has been squeezed out under the state of this stress. Therefore, the difference of fluoride increment of about 2.5 mg/l during 1990－1992 could be regarded as the additional fluoride (fluoride contribution) which was released from the compressing layers. Additional fluoride refers to the additional 2.5 mg/l fluoride added into the exploited geothermal water. Thus, the mass balance equation of fluoride can be listed for the porous solution (released water) and normal recharge runoff before and after their mixing. The solution of the equation indicates that about 40 percent geothermal water extracted is released water resulting from the land subsidence, in which about 32 percent is released by sandy soil with recovery deformation, and about 8 percent by sandy clay with irreversible deformation.

Silica content trends in Tanggu geothermal water also contain the artificial environmental imprint. Silica in all geothermal waters in Tanggu is in equilibrium with respect to chalcedony, thus it is possible to calculate the reservoir temperature by use of the chalcedony geothermometer, so as to verify the impact of production volume on reservoir temperature, between 1991 and 1995 (Figure 4).

The dash line in Figure 4 is used to verify the reliability. The verification method is: extrapolating the curve to the zero production point at which the temperature is equivalent to the reservoir temperature before exploitation. The temperature of 71℃ for the reservoir in the initial stage is obtained by extrapolation method. This result is in agreement with the available data and indicates that the extrapolation is reliable. A temperature drop 7℃ is now observed. The temperature drop might result from two factors. One is the entering of the great amount of released water with lower temperature due to the shallower buried depth; the other is that heat-balance between recharge runoff and surrounding rocks can not be reached, with the increase of production. Figure 4 also indicates that the reservoir temperature dropped quickly before 1993, and slowly after 1993. When the production rate is 4,000,000 m^3/a, the reservoir temperature is temporally stable at about 64 ℃ due to joint effect of the above mentioned factors.

Compressive strata exist in the Tanggu geothermal field where long term overexploitation caused land subsidence, which impacted the fluoride and silica contents. In the following paragraph, data from the Xiaotangshan geothermal field will be used to discuss the effect of long term overexploitation on the chemistry of a reservoir in incompressable basement rock.

The Xiaotangshan geothermal reservoir is located in siliceous dolomite of Proterozoic age penetrated by a Mesozoic granite stock. The thickness of overlying Quaternary formation is only tens of meters. Monthly sampling and chemical analysis for one production well were carried out in the 1960s (Jan. 1962 to Mar. 1967) and in the 1980s (Jun. 1987 to May 1990) respectively. At this site, the artesian discharge of thermal spring was 320,000 m^3/a in the 1950s and 1960s. In the 1970s, a pump was used to extract geothermal water for space heating. There were 8 production wells in the 1980s, and the total pumpage in 1987, 1988, and 1989 was 900,000, 1,080,000, and 1,200,000 m^3 respectively. The production rate is 3 to 3.5 times as much as the artesian discharge. As a result of increased pumping: hardness is increased, fluoride, sulphate and TDS are decreased; no distinct change observed for other species. To verify this hypothesis, correlation statistics of monthly Mg, F, and SO_4^{2-} concentrations in the 1980s with respect to the pumpage has been performed. Correlations of high confidence for the three components were obtained. The graph for magnesium is representative (Figure 5). To interpret this result, a mathematical model could be used for calculating the amount of Mg^{2+} leached from dolomite (main component of reservoir) in flowing fluid with variable velocity (to simulate the extraction rate in production wells). The calculations coincide roughly with the observed data. The slight error may result from ignoring the water temperature variation at the discharge area resulting from a change of flow rate in the deep aquifer. The measured magnesium concentration and artesian discharge under the natural state in the 1950s are marked. This initial state without production interference is in line with parabolic trend under the pumping state.

4. ANNUAL PRECIPITATION EFFECT ON CHEMICAL REGIME OF GEOTHERMAL WATER

The Taihang Mountains and Xishan Mountain, which define the western boundary of the North China Plain (See Figure 1), are the main recharge areas of the rivers groundwater, and geothermal water. As the Xiaotangshan geothermal field and Shijiazhuang city both stand on the edge of the plain, and are close to the Mountains, there is a certain similarity on hydrometeorology process.

In the North China Region, the relationship between precipitation and the recharge of normal temperature groundwater can be revealed by using tritium as a tracer. The tritium precipitation regime in the North China Region has been observed at the Shijiazhuang monitoring station. The annual curve of tritium concentration in precipitation shows (Figure 6a) three peaks (b, d, and f) and three valleys (a, c, and e). Niangziguan spring is a cold karst spring located at the edge of the basin, and its tritium content is undoubtedly influenced by local precipitation. Comparing the peaks and valleys of tritium in precipitation with those of the spring, we can find that the time lag of precipitation recharge for this spring is about one month.

In Xiaotangshan geothermal field, the highest temperature is 65℃ at the wellhead, and the thermometric temperature of the reservoir is of 80℃. The space heating season begins in November and ends in the following March. During the heating period, the monthly production is up to 2 times as much as the non-heating period. Based on the monthly monitoring data of sodium, potassium, calcium, and magnesium, the activities of these cations are shown on

Figure 6b. The upper and lower boundaries are defined by calculating the activity at 50 ℃ and 150 ℃, which approximate the wellhead and reservoir temperatures. The annual curves for cation activities also consist of three peaks (b2, d2, and f2) and three valley (a2, c2, and e2), that show the time-lag of precipitation recharge for this geothermal site is about 4 months (Figure 6b).

At the Tanggu geothermal site, sampling monitoring has been carried out annually, making it difficult to eliminate the effect of random factors for a well. Therefore, seven wells (TR1, 2, 3, 4, 5, 8, 9) are selected as a "gang of wells" and the average water chemistry changing with time has been studied. A positive correlation between TDS and annual precipitation for all the seven wells is present (Figure 7).

There are the natural environmental imprints, such as seasonal and yearly distribution of local precipitation involved in the chemistry of low-temperature thermal waters. The dynamic mechanism for this effect may be pressure transfer, i.e., the geothermal fluid is driven by pressure, which is relatively high in plentiful water periods, and is relatively low in low-water periods from the recharge areas.

5. PALEOCLIMATIC EFFECT ON CHEMICAL REGIME OF GEOTHERMAL WATER

Forty ^{14}C data together with ^{18}O values in low-temperature thermal water have been obtained. These values represent many geothermal sites on the North China Plain. The depth and time of the sampling range from 500 m to 3,400 m and from 1980 to 1990 respectively. And the ^{14}C ages range from modern to 35,000 years B.P.

Contours of ^{14}C ages are drawn out in terms of the sampling location. The flow direction of geothermal runoff shown by the contours of ^{14}C ages is in line with conclusions deduced from that of TDS and of the pressure head of thermal waters. By using these criteria, the confidence of the dating data are verified.

Figure 8 shows the relationship between age and oxygen isotopes. The curve can be divided into three fractions. ^{18}O values for the d-c part of the curve decreases with low change frequency and big amplitude; for c-b, ^{18}O value increases, with high change frequency and small amplitude; there is an abrupt increase of ^{18}O value from b to a, afterwards, it seems that there is a decrease trend. On the curve, there are two joints, i.e. point a, which is equivalent to the stage changing into warm period of Holocene after the last glacial period, and point c corresponding to the beginning stage of the dry-cold glacial period.

The tendency and turning time of the paleoclimate change recorded by the geothermal water in the North China Region, coincides with some paleoclimate records from loess, deep sea deposits, but a little difference on the turning time compared with the records from lacustrine deposits at Qinghai-Tibet Plateau.

6. CONCLUSIONS

1. In addition to the interaction between water and rock, there are various environmental imprints affecting the chemical composition in the low-temperature geothermal waters in a great sedimentary basin of Cenozoic age: 1) When land subsidence and strata compressing occurred due to overproduction, a large amount of released water with certain chemical compositions had entered into geothermal water, 2) Some changes of certain chemical composition are caused by increase of production or the change of local precipitation distribution, 3) When the isotopic constituents of hydrogen and oxygen in low-temperature thermal waters was not coincident with the meteoric water line, that can be interpreted not only by such as deuterium surplus or oxygen drift or evaporation, but by the imprint of paleoclimate at the recharge period as well. Revealing the environment imprints on chemical regime is beneficial to carry out relevantly the chemical interpretation in exploration.

2. To discriminate the artificial environment imprints on the chemical regime of geothermal water is beneficial to make out the forewarning of overexploitation in the early stage (within 1-2 years) in a project. And it is undoubtedly helpful to ensure the sustainable development of geothermal energy.

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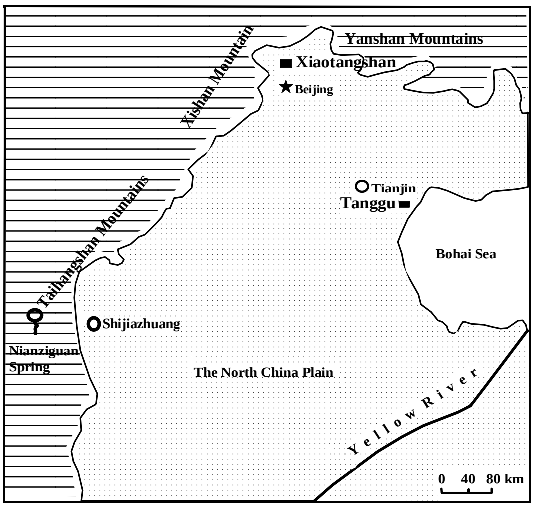


Figure 1. Location Map

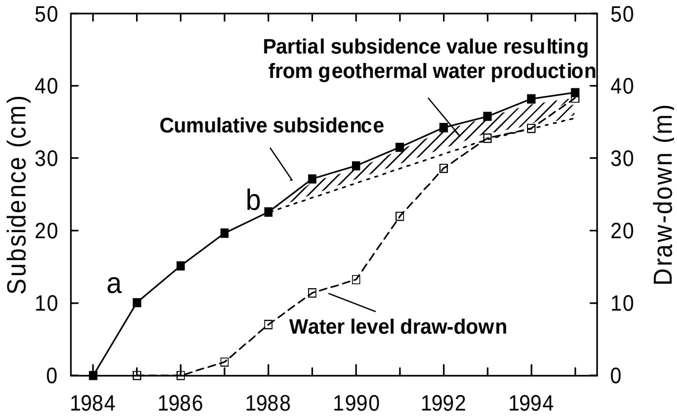


Figure 2. Observed land subsidence and water level draw-down (TR-10) in Tanggu (Modified from G. Axelsson, 1996)

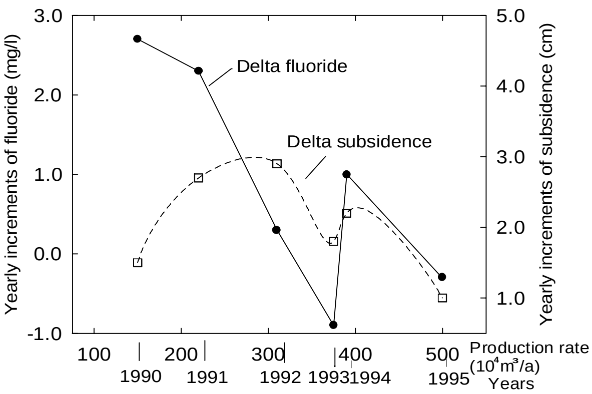


Figure 3. Changes in delta fluoride of geothermal water and in delta subsidence versus production rate at Tanggu

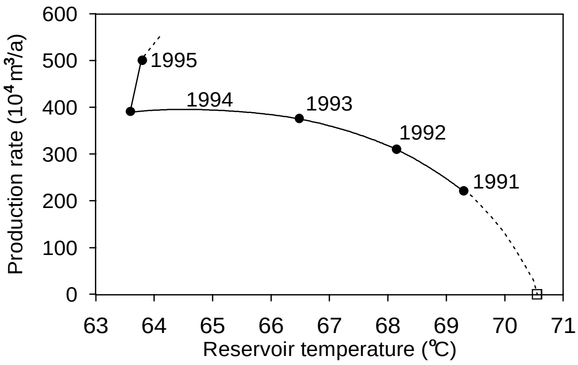


Figure 4. Yearly change in reservoir temperature (by chalcedony geothermometer) versus production rate at Tanggu

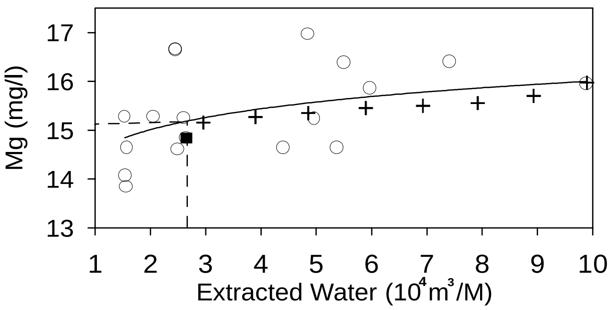
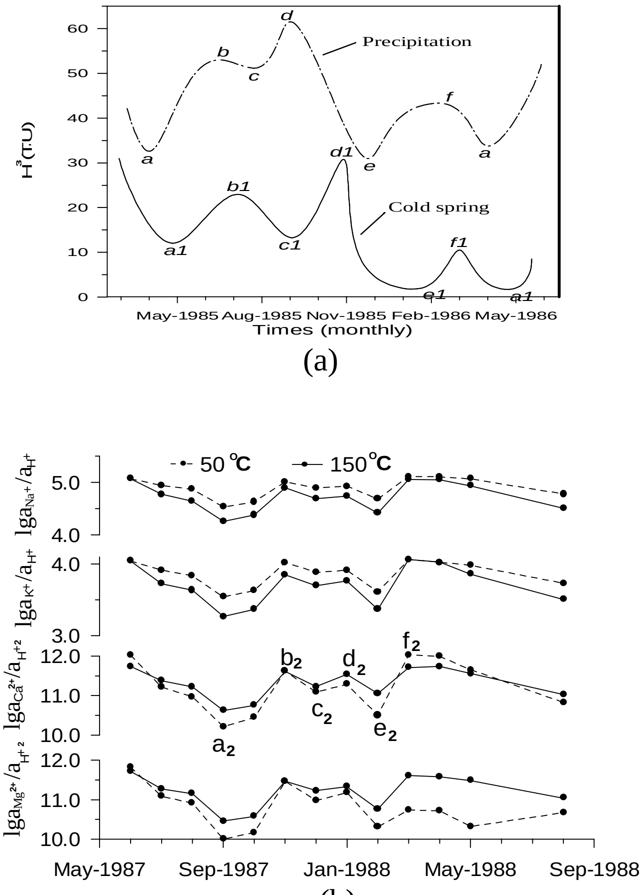


Figure 5. Plot of Mg concentration of geothermal water versus production monthly rate from well No. 1, Xiaotangshan.

The solid line is a correlation curve based on observed values (the circles); cross is value by calculation; square and dashed line indicate artesian discharge of spring No.1 in the 1960s and the Mg corresponding concentration



(a)

(b)

Figure 6. Regime patterns of yearly tritium from the Niangziguan Spring and from precipitation in Shijiazhuang, which coincide with that of hydrochemistry from monthly sampling at Xiaotangshan.

The letters a through f mark the characteristic points for hydro-meteorological process and the response each other

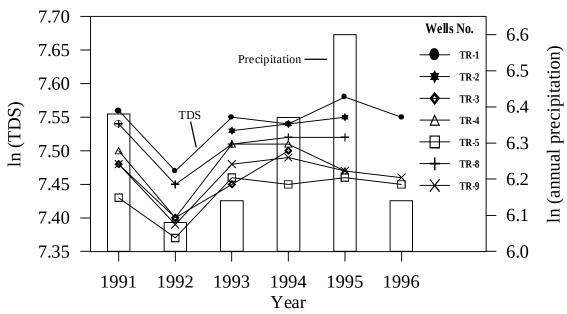


Figure 7. Yearly changes of TDS(in ppm) in thermal water from some production wells at Tanggu versus annual precipitation amount (in mm; at Tianjin)

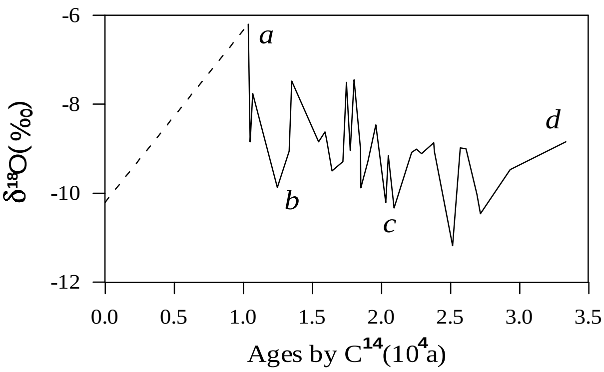


Figure 8. Paleoclimate record of geothermal water of North China (Yao, 1995).

d-c: The last glacial period in China, climate had been translated wet-warm into dry-cold. c-b: During the glacial period, the climate was dry-cold. b-a: Be transferred to wet-warm and the Holocene just started.