APPLICATION OF STABLE ISOTOPES TO HYDROGEOLOGY IN COAL MINE

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Abstract

Stable isotopes including Oxygen-18 and Deuterium have been applied to investigation of hydrogeology in main coal mines.

By determination of stable isotopic composition of hydrogen and oxygen together with water analysis, the following studies have been developed:

Identification of the hydrogeochemical characteristics of the groundwater from varied aquifers;

Analysis of the hydraulic relationship between varied aquifers;

Interpretation of the probable recharge source of mine water.

The research results mentioned above reveal that:

1. The groundwater from main aquifers at coal mines in north China is of meteoric origin, which is recharged from hilly area surrounding the coal mine. Its isotopic composition differs slightly from that of the local precipitation.
2. There is a mutual hydraulic relationship between the Ordovician and Quarternary aquifers, so the difference of isotopic composition is very small.
3. By way of the variation of isotopic composition of groundwater from coal-bearing strata, we can infer the hydraulic relationship extent between overlaid alluvial layer and underlaid Ordovician limestone.

Introduction

In recent years, environmental isotopes are becoming important in hydrogeological studies of surface and ground water. They have been applied to hydrogeological research of main coal mines in North China and the stable isotopic study is an auxiliary medium to complement the classical techniques of hydraulics and hydrochemistry.

The purposes of this method are as follows:

1. Studying the origin of groundwater from varied aquifers at the study area;
2. Analysing the hydraulic relationship between varied aquifers;
3. Defining the probable sources, flow and passage-way of mine water;
4. Checking and replenishing the conclusion of hydrogeological and hydrochemical methods.

In this paper, the application of Oxygen-18 and Deuterium isotopes indicates:

1. The groundwater from main aquifers (Ordovician limestone, Quarternary alluvial deposit and coal-bearing strata) is of meteoric origin, and it is recharged from hilly area surrounding the coal mine. The data from determination of isotopes have shown that the circulating condition is good (The depth is shallow and the period is short as well).
2. The same recharge area and the mutual hydraulic relationship have been identified for both Ordovician and Quarternary aquifers with little difference in isotopic composition.
3. By way of the variation of isotopic composition of groundwater from coal-bearing strata, we can infer hydraulic

relationship between the overlaid alluvial layer and underlaid Ordovician limestone.

4. To combine isotopic study with hydrochemistry enabled us to recognize the characteristics of classification of groundwater from varied aquifers.

Groundwater comes from the penetration of modern precipitation and surface water, from the surviving ancient subterranean water and sometimes from the sea water intrusion.

The isotopic composition of groundwater depends on the mixing action and mixed degree of modern precipitation with ancient penetrating water, depositional water, evaporated water, sea water and so on, therefore, mixing action plays a basic role.

The stable isotopes Oxygen-18 and Deuterium are of great significance for the hydrogeological research, the isotopic variations of hydrogen and oxygen are expressed in parts per thousand (permil) different from the standard, SMOW:

$$\delta^{18}O = \left[\frac{(^{18}O/^{16}O)\ \text{sample}}{(^{18}O/^{16}O)\ \text{SMOW}} - 1 \right] \times 1000‰$$

$$\delta D = \left[\frac{(D/^{1}H)\ \text{sample}}{(D/^{1}H)\ \text{SMOW}} - 1 \right] \times 1000‰$$

The determination is performed by MAT-251 mass spectrometer and the precision of measurement about 0.1‰ for ^{18}O and 1‰ for D, this is equivalent to 0.16 ppm fluctuation for D and 0.2 ppm for ^{18}O.

It is unsuitable that the water sample is injected directly into the mass spectrometer. Before determining the water sample, it should be converted into carbondioxide (CO_2) or hydrogen (H_2).

For preparing the hydrogen (H_2) sample, water is passed through the heated Zinc (Zn) or Uranium (U) and it reduced into H_2, which is afterward injected into the instrument. The basic reaction is,

$$Zn + H_2O \xrightarrow[\text{Vaccum}]{400^\circ C} ZnO + H_2\uparrow$$

The CO_2 sample is prepared by exchanging oxygen isotopes from water and carbon dioxide. The reaction is carried out as follows,

$$H_2O^{18} + C^{16}O^{16}O \xrightarrow[\text{oscillation for 4 hours}]{\text{thermostant }(25^\circ C)} H_2O^{16} + C^{16}O^{18}O\uparrow$$

Study of characteristics of main aquifers at Kailuan Coal Mine

Brief introduction of hydrogeology conditions concerning aquifers

The study area is located at the northeast plain of Hebei Province and lies in the middle of alluvial fan of Luan River. Most of the area is covered with Quarternary alluvium(Q), Ordovician limestone exposes locally in the north hilly land.

The alluvium and Ordovician limestone aquifers are mainly water-bearing strata. The bottom of alluvium aquifer is coarse gravel bed which is rich in good quality of water. The upper part of the alluvium near the surface is phreatic aquifer, which is closely related with the surface water and easily subjected to pollution from the surface.

The coal-bearing strara belong to the Carboniferous-Permian system (c.p) with a number of coal seams, sandstones and shale beds. The sandstone beds containing groundwater form aquifers. Among them there are two main aquifers, one is the sandstone bed as the roof of No.5 coal seam and the other is the bed between No.12 and No.14 coal seams.

Underlying Ordovician limestone aquifer is the basement of the coal-series strata. As it directly receives the rainfall recharge from outcrop area, this karstifiable basement is rich in groundwater and has become confined aquifer. Because of the existence of the faults and columns of depression,the confined water often rushes up into the pit and causes dangerous gush. The water from Ordovician limestone under better circulating conditions is lower in total dissolved solids (T.D.S.), good in quality and rich in yield.

Interpretation of isotopic data from study area

There are eight mines within the study area. Various water samples from every stratum have been collected and analysed,and the isotope determination of water is performed together with water analysis. The ^{18}O and D contents of water samples are listed in Table I-VI, the results of classification are listed in these tables according to their hydrochemical characteristics. The hydrochemical characteristics of groundwater from every stratum are shown in Table VII.

Fan Gezhuang Coal Mine

Table 1 listed isotopic values of $\delta^{18}O$ and δD is shown in Figure 1-1. All of groundwater samples (alluvium, coal-bearing strata and Ordovician limestone) fall on both sides of the meteoric water line, this means that the relationship between $\delta^{18}O$ and δD conforms with the formula $\delta D=8\delta^{18}O+10$. The least square best fit line through these points is expressed by equation $\delta D = 7.93\delta^{18}O + 10.67$, $r = 0.73$. Therefore these groundwaters are of meteoric origin.

But sites of the samples from coal-bearing strata differ slightly from those which represent other aquifers. So they tend to go down left of the meteoric water line, showing the oxygen-18 and Deuterium contens are lower than others. In addition, the sites of the samples which are collected from surface water of depression are away from the range of subsurface water and apart from the meteoric water line, showing the slight influence of evaporation effect. The relationship between ^{18}O and D of these samples is described by the equation $\delta D = 7.2\delta^{18}O + 4.23$, the slope is less than 8. The deviation of rainfall sample indicates statistical random property and the scattered degree will be reduced intensely by the dispersion action of groundwater.

The detailed illustration of co-variation of ^{18}O and D in groundwater of each aquifer is shown in Figure 1-2. On the basis of the scattered distribution, the isotopic values have been divided into three parts: Quaternary alluvium: $\delta\bar{D} = -58.9$‰, $\delta^{18}\bar{O}=-8.61$‰, Ordovician limestone: $\delta\bar{D}=-56.8$‰, $\delta^{18}\bar{O}=-8.58$‰, Coal-bearing strata: $\delta\bar{D}=-63.5$‰, $\delta^{18}\bar{O}=-9.15$‰ (Considering the hydrogeological data and hydrochemical classified results, we take the samples 5, 10, 11 which differ from others in isotopic values as representation of coal-bearing strata and give the average isotopic value.). It may be seen as follows:

1) $\delta^{18}O$, δD values of alluvium accord with Ordovician, this means the recharge sources are at the same area, under certain conditions the water from Ordovician can mix with that from alluvium by various structures, such as faults and fissures. As a result, the difference between isotopic values is very small.

2) The typical water samples from coal-bearing strata (samples 5, 10, 11) have lower values ($\delta\bar{D} = -63.5$‰, $\delta^{18}\bar{O} = -9.15$‰), the reason for this is probably the mixing effect caused by percolating water from overlaid alluvium and raising water from underlaid Ordovician limestone aquifer. The aquifers of the coal-bearing strata, though there left some ancient percolating water which has depleted heavy isotopes, are filled up with modern precipitation after a number of hydrologic cycles, and their isotopic value is close to that of the modern precipitation.

3) The isotopic values of samples 6,7,8,9 of coal-series fall into the value range of Ordovician or Quaternary . That shows obviously the hydraulic relationship between the two aquifers. By means of the test of hydrochemical trace, it has been discovered that water inflow sites (Sample 1291, 1321, 1497 at -320 level) are connected with alluvium and under the influence of water from Ordovician aquifer, other sites (Sample 6,7,204, 206 at -450 level) are characterized by water quality of Ordovician aquifer.

Figure 1-3 shows the co-variation of $\delta^{18}O$ and δD versus depth in Fan Gezhuang Coal Mine. The curves display that the water from coal-series has the obvious tendency of depleted heavy isotopes (^{18}O, D), but under the influence of mixture, some samples (No. 6,7,8,9) also display the centain fluctuation. The isotopic values of Ordovician limestone and alluvium centered on a narrow range and the variation is very small.

The penetrating altitude of rainfall recharge area can be estimated by the altitude effect:

$$H = \frac{\delta s - \delta p}{K} + h \qquad (1)$$

where

H = the height of recharge area (m),

δ_s = the $\delta^{18}O$ content of groundwater from Ordovician limestone aquifer (-8.58‰),

δ_p = the mean annual $\delta^{18}O$ content of local rainfall (Here we take the isotopic value of the phreatic aquifer as representation of average value of rainfall, δ_p = -7,95‰),

K = the elevation gradient of isotope ^{18}O (-0.3%/100m),

h = the elevation of study area (+32 m), as a result

$$H = \frac{-8.58 + 7.95}{-0.3/100} + 32 = 242\ (m).$$

By judging the geomorphic feature, it is possible that Qing Lingshan hill, Weishan hill at the north part of study area, with the outcrop of Ordovician limestone aquifer, are the rainfall recharge area. Because the recharge area is near to the discharge area,the isotopic values of groundwater are close to those of local rainfall, at the same time, the variation of isotopic value is small which it could be characterized by fine water quality and lower total dissolved solids. These evidences show that both groundwater and rainfall are related closely.

Zhao Gezhuang and Tang Jiazhuang Coal Mine

There are faults and shear zones frequently appearing in the coal-bearing strata with a thin alluvium in this region. Therefore, the groundwater from alluvium and Ordovician limestone has an influence upon the isotopic contents of water from coal-series, as a result the isotopic values are rising, most of which fall into the value range of Ordovician limestone or alluvium aquifers.

Figure 2-1 and 3-1 are distribution charts for δD in groundwater from Zhao Gezhuang and Tang Jiazhuang, respectively. In Figure 2-1, Sample 2 (δD = -53.2‰) (the sandstone roof of No.1 coal seam) is significantly affected by the alluvium aquifer, and Sample 1,3,4 (coal-series) are also with increased δD content ($\delta\bar{D}$ = -58.41‰). This value may be compared with that (-63.53‰) from Fan Gezhuang and the variation in δD content is 5‰.

Figure 3-1 shows the increased change of δD value in water from Tang Jiazhuang. Samples 6,7 are obviously influenced by mixture with water from Ordovician limestone and the δD values are identical with each other. In addition, the water quality of Sample 6 already belongs to the type of mixing water from coal-series and Ordovician limestone.

Figures 2-1a, 3-1a are variation diagrams of δD versus depth. The figures show that the δD contents of coal-bearing and overlaid or underlaid layers make an unremarkable difference, and mixing degrees of water from each stratum are higher.

Lu Jiatuo Coal Mine

Figure 4-1 is a distribution chart for δD in groundwater, among them, the water from coal-series has an average δD of -65.8‰, the water from Ordovician limestone -59.67‰ and from alluvium -56.5‰ . Sample 5 represents the phreatic aquifer, it has the value of -53.6‰. Combining with the results of hydrochemical analysis, we can see that Samples 7,9 are representatives of coal-series water and Samples 6,8,10 are affected by alluvium and the Ordovician limestone aquifers respectively. The water quality of Sample 6 belongs to the mixing type, Samples 8, 10 are the water taken from the Ordovician limestone.

The above conclusion is also obtained from Figure 4-1a, the isotopic values measured from Samples 1,2,3,4 are situated in the value range of alluvium, those from Samples 7,9 represent the value range of water from coal-bearing strata and from Samples 11,12,13 have the value range of water from Ordovician limestone. Samples 6,8,10 themselves demonstrate that they are the water mixed to varying degrees.

Qian Jiaying Coal Mine

Because there is a thick Quàternary aquifer above coal-series, the coal-bearing strata may receive directly the penetrating recharge from overlaying aquifer.

Figure 5-1 shows distribution chart for δD in groundwater from Qian Jiaying. In alluvium the δD is -55.8%o and in coal-series the δD vary between -57.9%o and -67.7%o. Taking $\delta \bar{D}$ (-65.7%o) of the Samples 5,6 from the coal-series as an example, we can see from Figure 5-1 that Samples 3,4 are the mixed water and the deeper the water is, the lower the mixing degree becomes. At the -450m level, the isotopic value of Sample 5 already falls into the typical value range of coal-series, as that of the Sample 7 from Ordovician limestone aquifer. Because of the stoppage in the middle part of the well, either of isotopic content(δD=-63.1%o) or water analysis belongs to the range of coal-bearing strata.

If we assume that δD in alluvium is at one of both sides (δD = -55.8%o) and δD in coal-series is at another end (δD = -65.7%o), the mixing ratio of samples 3,4 will be estimated:

$$C_{mix} = \frac{Am + Bn}{m + n} \qquad (2)$$

where

A = the δD of water sample from alluvium aquifer
B = the δD of water sample from coal-series aquifer
C = the mixing water δD
m = the percentage of water from alluvium aquifer
n = the percentage of water from coal-series aquifer

for Sample 3

$$m_3 = \frac{100\ (C-B)}{A-B} = \frac{100 \times (-57.9 + 65.7)}{-55.8 + 65.7} = 78.15\%$$

for Sample 4

$$m_4 = \frac{100\ (C-B)}{A-B} = \frac{100 \times (-62.0 + 65.7)}{-55.8 + 65.7} = 36.78\%.$$

The similar results will be obtained by the method of illustration (see Fig. 5-2). As a result, utilizing the isotopic values we can estimate the samples 3,4 contain about 78% and 37% of water from the alluvium aquifer respectively.

Figure 5-1a is a variation diagram of δD versus depth. In Figure 5-1a, samples 5,6 reflect the isotopic contents in groundwater from coal-series (δD=-64.7%o and δD=-67.7%o), samples 3,4 are influenced by alluvium water (δD =-58.0%o and δD = -62.1%o), and sample 7 is from Ordovician limestone water with a characteristic of coal-sereis water.

Lin Nancang Coal Mine

This area is far from the mines mentioned above and belongs to another hydrogeological unit. The determination of isotopes indicates that isotopic values of every stratum have respectively obvious distribution range. In Fig. 6-1 and Fig. 6-1a, the alluvium water ($\delta\bar{D} = -61.5‰$), the Ordovician limestone water ($\delta\bar{D} = -65.0‰$), and the coal-series water ($\delta\bar{D} = -73.2‰$) could be distinguished easily. The isotopic contents between water from alluvium and Ordovician limestone have a difference, this shows the recharge source of alluvium aquifer is distinct from those of Ordovician limestone aquifer and there exists no hydraulic relationship between the two aquifers.

According to the formula(1), the elevation of permeable recharge areas will be given and the altitude difference of recharge areas is:

$$HO_2 - HQ = \frac{\delta SO_2 - \delta P}{K} - \frac{\delta SQ - \delta P}{K} = \frac{\delta SO_2 - \delta SQ}{K}$$

$$= \frac{-65.0 + 61.5}{-2.5/100} = 140 \text{ (m)}$$

In this area, except for Sample 7, the coal-series water are not affected by the alluvium or Ordovician limestone aquifer and its δD content maintains the somewhat small negative value ($\delta D = -73.2‰$).

Conclusion

Except for Lin Nancang, Table 8 listed the δD, $\delta^{18}O$ general average values of each main aquifer at Kai Luan Coal Mine.

On the basis of Table 8 (see Table 8), we have drawn the variation diagram of δD, $\delta^{18}O$ versus depth (Fig. 7-1), and it may be considered that:

1. Variations of δD and $\delta^{18}O$ observe similar regulations;
2. δD and $\delta^{18}O$ contents of water from alluvium aquifer are similar to δD, $\delta^{18}O$ contents of water from Ordovician limestone aquifer;
3. In comparison with the groundwater from other two aquifers, the groundwater from coal-bearing strata depleted the heavy isotope D by 7‰ and the heavy isotope ^{18}O by 0.5‰..

Because the δD, $\delta^{18}O$ values of groundwater at Kai Luan Coal Mine conform with formula $\delta D = 7.9\delta^{18}O + 10.7$ and fall on the meteoric water line, so the recharge source is precipitation. There is not any other groundwater which is of non-meteoric origin. The occurrence of lower isotopic values of coal-bearig strata is attributed to the mixing action of the modern rainfall and surviving ancient percolating water.

By means of the difference of isotopic values between aquifers, the local rainfall and formula (1), the altitude of recharge area can be estimated. If we take the δD ($\delta^{18}O$) content of Ordovician limestone water as one end of two-component and the δD ($\delta^{18}O$) content of coal-series as another end, according to the formula (2), the mixed ratio can be calculated.

The hydrochemical method is a basic method for classifying groundwater, but the isotope method will complement the classical technique in view of the special feature of isotopes. It is possible for us to determine the source and passage-way of mine water, and estimate the mine water inrush flow on the basis of more detailed isotopic data from tests.

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Table I. Oxygen-18 and deuterium isotope data for aquifers, Fan Gezhuang Mine (10-11, 1985)

Sample Number	Sample Location	Stra-tum	Groundwater Classification	$\delta^{18}O$ ‰	δD ‰
1	Q. well 11 #	Q	Alluvium	-8.78	-60.4
2	Q. well 14 #	Q	Alluvium	-8.64	-60.2
3	Q. well 10 #	Q	Alluvium	-8.40	-55.9
4	supply well O_7#	Q	Alluvium	-7.59	-59.2
5	S-350 5^S (pit)	P	Coal-series	-9.46	-65.2
6	-450.2171 7^S(pit)	P	O_2-coal(mixing)	-8.98	-59.8
7	-450.2176 7^S(pit)	P	O_2-coal(mixing)	-8.66	-55.7
8	S-350-3 9^S (pit)	P	Coal-series	-8.95	-57.4
9	S-350-2 9^S (pit)	P	Coal-series	/	-57.1
10	S-350-3 12^S (pit)	C	Coal-series	-8.92	-63.3
11	S-350-4 12^S-14^S(pit)	C	Coal-series	-9.08	-62.1
12(1/11)	O. well 7#	O_2	O_2	-8.42	-59.9
13(15/11)	O. well 7#	O_2	O_2	-8.53	-56.5
14(14/11)	O. well 7#	O_2	O_2	-8.45	-56.2
15	supply well(school)	O_2	O_2	-8.72	-56.3
16	supply well 1#	O_2	O_2	-8.74	-56.7
17	O. well O_1	O_2	O_2	-8.59	-55.3
18	N-depression	ground	Surface mixing	-6.26	-42.6
19	S-depression	ground	Surface mixing	-4.87	-31.0
20	W-depression	ground	Surface mixing	-5.85	-37.0
21	E-depression	ground	Surface mixing	-3.98	-25.0
22(18/11)	Fan mine rainfall	/	Rainfall	-10.24	-61.3

Table II. Deuterium isotope data for aquifers, Zhao Gezhuang Mine

Sample Number	Sample Location	Stratum	Grounderwater Classification	δD ‰
1	0382 - 1^{s} well	P(sandstone)	Coal-series	-57.0
2	0387 - 1^{s} well	P(sandstone)	Coal-series	-53.2
3	E. 0450 5^{s} (pit)	P(sandstone)	Coal-series	-60.6
4	E. 1179 98^{m}(pit)	P(sandstone)	Coal-series	-57.6
5	W. 9 tunnel well (pit)	O_2	O_2	-59.2
6	4 tunnel well (pit)	O_2	O_2	-54.6
7	observation well(school)	O_2	O_2	-55.8
8	observation well(Reng Yuan)	O_2	O_2	-55.9
9	W. 10 tunnel well (pit)	O_2	O_2	-56.8
10	observation well (302 plant)		O_2	-54.5
11	Sui - well 7		O_2	-54.8
12	Sui - well 5		O_2	-55.4

Table III. Deuterium isotope data for aquifers, Tang Jiazhuang Mine

Sample Number	Sample Location	Stratum	Groundwater Classification	δD ‰
1	water-53 well	Q(gravel)	Alluvium	-59.0
2	water-42 well	Q(gravel)	Alluvium	-61.6
3	supply well(Ai Jia)	Q	Alluvium	-58.3
4	water - 51 well	Q(gravel)	Coal-series	-59.4
5	Xu - 10 well	P(A-5^{s})	Coal-series	-62.2
6	N - 340, 12^{s} (pit)	C	Coal-O_2(mixing)	-58.7
7	well 3 (lianxi)	C(14^{s})	Coal-series	-56.7
8	E. WII.2	O_2	O_2	-57.4
9	E. WI. 1	O_2	O_2	-58.6
10	supply well(pit)	O_2	O_2	-57.6
11	supply well 1(Lianxi)	O_2	O_2	-56.9
12	supply well 2(Lianxi)	O_2	O_2	-59.9

Table IV. Deuterium isotope data for aquifers, Lu Jiatuo Mine

Sample Number	Sample Location	Stratum	Groundwater Classification	δD ‰
1	well 1(cold storage plant)	Q(gravel)	Alluvium	-57.9
2	supply well (new)	Q	Alluvium	-57.2
3	supply well (Houyin)	Q	Alluvium	-55.6
4	supply well (S-part)	Q	Alluvium	-55.3
5	supply well (old)	Phreatic	Alluvium	-53.6
6	-425-4 5^S (pit)	P	Coal-alluvium(mixing)	-60.4
7	-600.4176 7^S (pit)	P	Coal-alluvium(mixing)	-65.8
8	-600-3 7^S (pit)	P	O_2	-57.4
9	-600.4219 14^s- K^3	C	Coal - O_2 (mixing)	-65.8
10	-800-1 12^S (pit)	C	O_2	-54.7
11	supply well (Heiyia)	O_2	O_2	-61.1
12	observation well ol	O_2	O_2	-60.5
13	-600-3 supply well(pit)	O_2	O_2	-59.3

Table V. Deuterium isotope data for aquifers, Qian Jiaying Mine

Sample Number	Sample Location	Stratum	Groundwater Classification	δ D ‰
1	Pumping well 5 #	Q	Alluvium	-56.7
2	Pumping well 3 #	Q	Alluvium	-54.8
3	water-5 # (-216m)	P (1^S)	Coal-series	-57.9
4	water-6 # (-310m)	P (s^S)	Coal-series	-62.1
5	-450-5^S (pit)	P (5^S)	Coal-series	-64.7
6	water-well 2 #	C (12^S-14^S)	Coal-series	-67.7
7	water-well 1 #	O_2	Coal-series	-63.1

Table VI. Deuterium isotope data for aquifers, Lin Nancang Mine

Sample Number	Sample Location	Stratum	Groundwater Classification	δD ‰
1	well 6 #	Q (sandstone)	Alluvium	-62.4
2	well 2 #	Q (sandstone)	Alluvium	-60.5
3	well 11 #	P (5^S)	Coal-series	-71.1
4	well 10 #	P (5^S)	Coal-series	-74.4
5	well 9 #	P (5^S-5A)	Coal-series	-73.8
6	W. -400 14^S-K^3(pit)	C	Coal-series	-73.0
7	well 4 #	C (14^S-K^3)	O_2	-69.1
8	well 8 #	O_2	O_2	-67.9
9	supply well 1-2 #	O_2	O_2	-67.0

Table VII. Hydrochemical data for aquifers, Kai Luan Mine

	Alluvium	Coal-bearing Strata	Ordovician Limestone
Classification of water quality	HCO_3-Ca.Mg	HCO_3-KNa HCO_3-CaMg.KNa SO_4HCO_3-CaMg	HCO_3 - Ca.Mg
Hardness (mg/l-$CaCO_3$)	53.3-249.5	9.0 - 71.5 109.0-285.0 267.5-1408.5	128.5-392.5

Table VIII. δD, $\delta^{18}O$ general average values of aquifers, Kai Luan Mine

	δD(‰) Sample Number	Mean	$\delta^{18}O$(‰) Sample Number	Mean
Alluvium	14	-57.98	3	-8.61
Coal-bearing strata	8	-64.71	3	-9.15
Ordovician Limestone	25	-57.17	6	-8.58

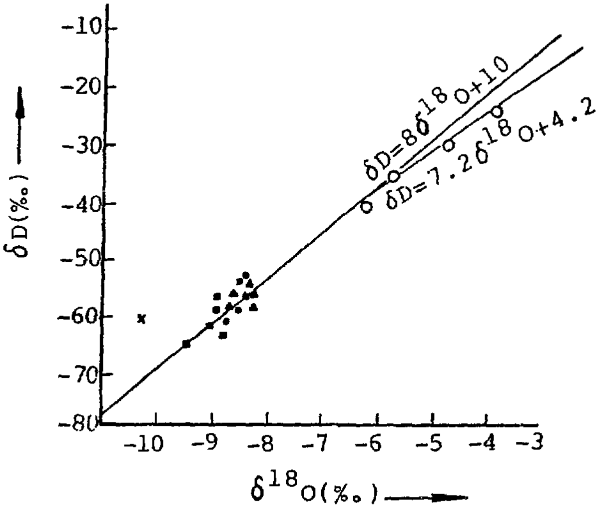


Fig. 1-1 Co-variation of deuterium and ^{18}O in groundwater of the aquifers, Fan Gezhuang Mine

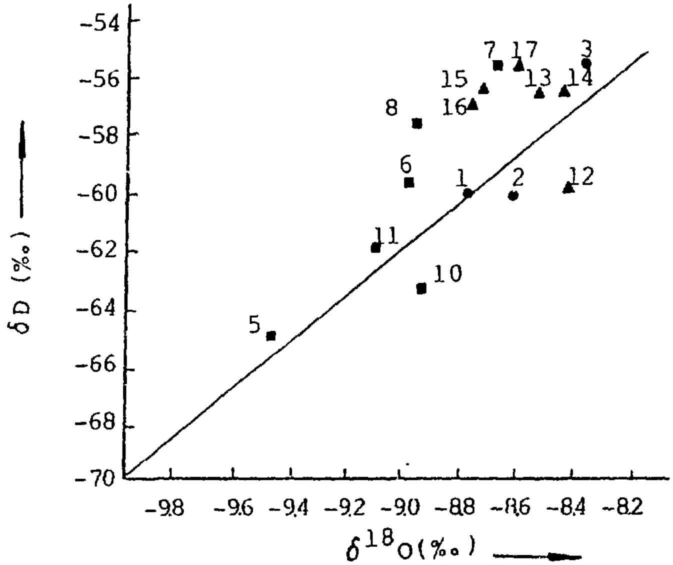


Fig. 1-2 Detail illustration of co-variation of deuterium and ^{18}O in groundwater

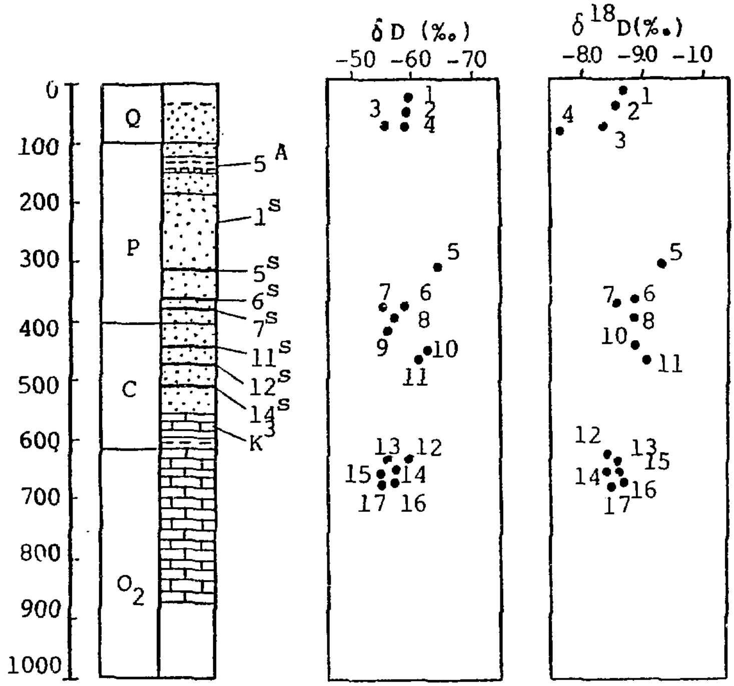


Fig. 1-3 Depth versus $\delta^{18}O$ and δD, Fan Gezhuang Mine (This stratigraphic column is representation of aquifer characteristics in the vicinity of Fan Gezhuang Mine.)

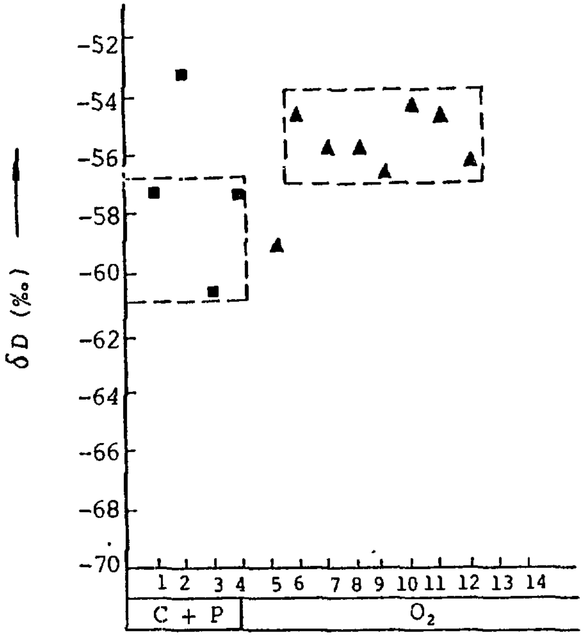


Fig. 2-1 The distribution chart for δD in groundwater from Zhao Gezhuang Mine

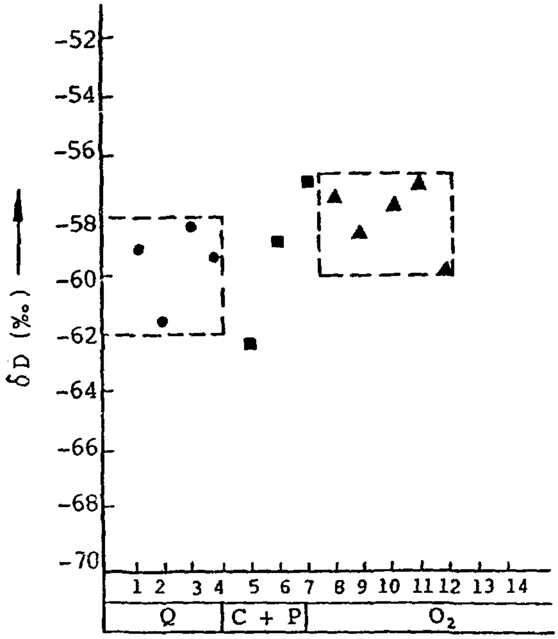
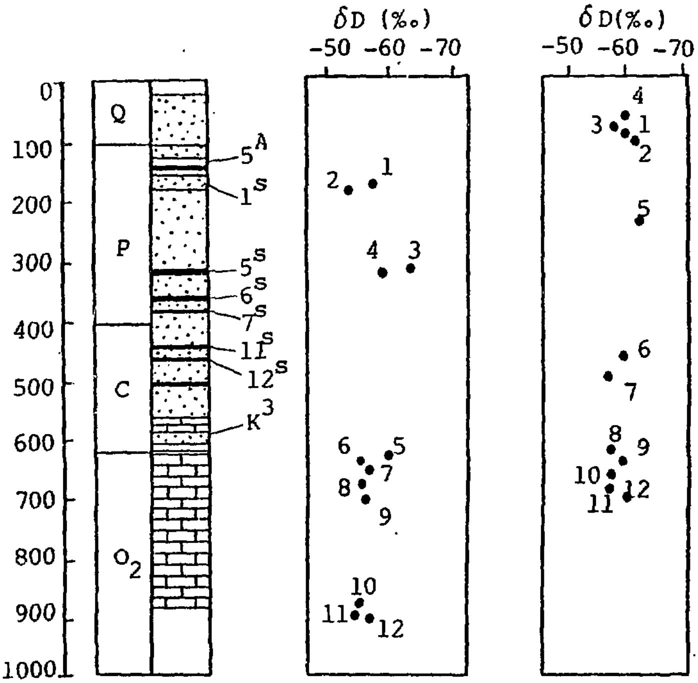


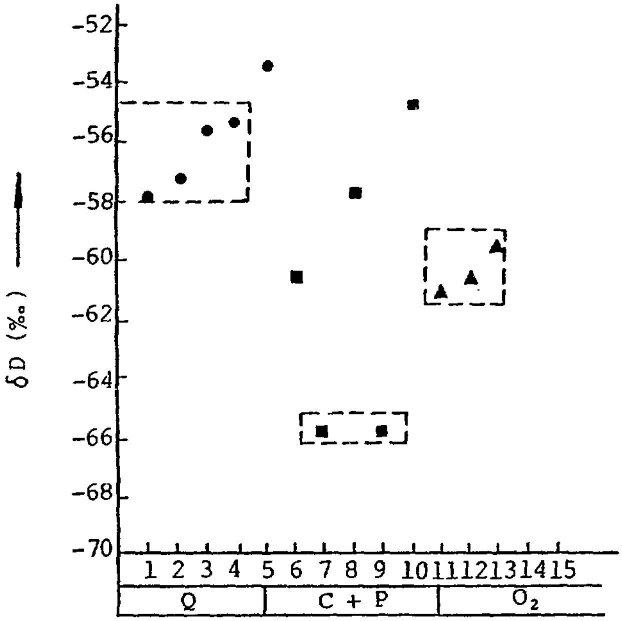
Fig. 3-1 The distribution chart for δD in groundwater from Tang Jiazhuang Mine



2 - 1a

3 - 1a

Figs. 2-1a, 3-1a Depth versus δD, Zhao Gezhuang and Tang Jiazhuang Mine, respectively



'Fig. 4-1 The distribution chart for δD in groundwater from Lu Jiatuo Coal Mine

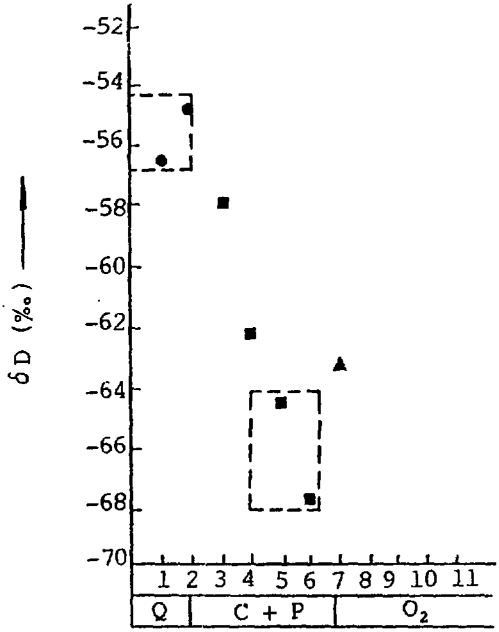


Fig.5-1 The distribution chart for δD in groundwater from Qian Jiaying Coal Mine

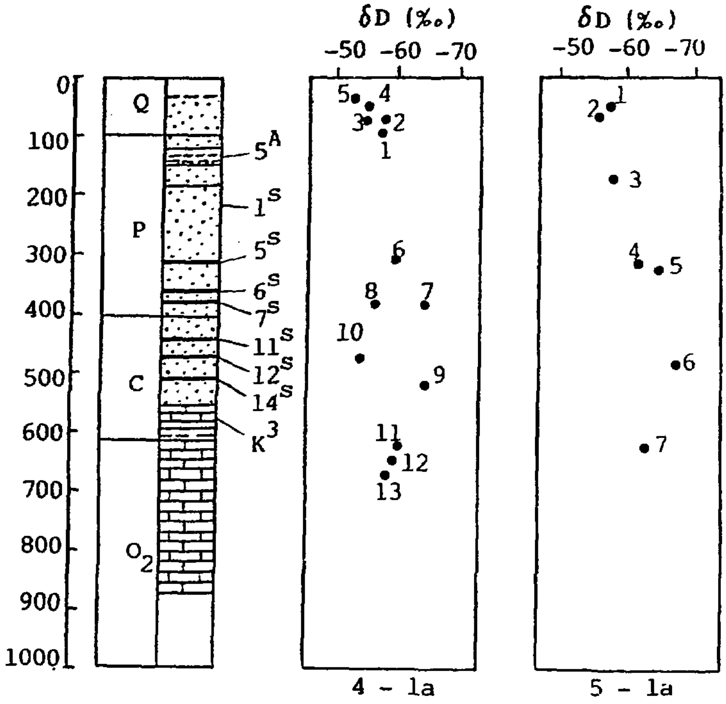


Fig. 4-1a, 5-1a Depth versus δD, Lu Jiatuo and Qian Jiaying Coal Mine

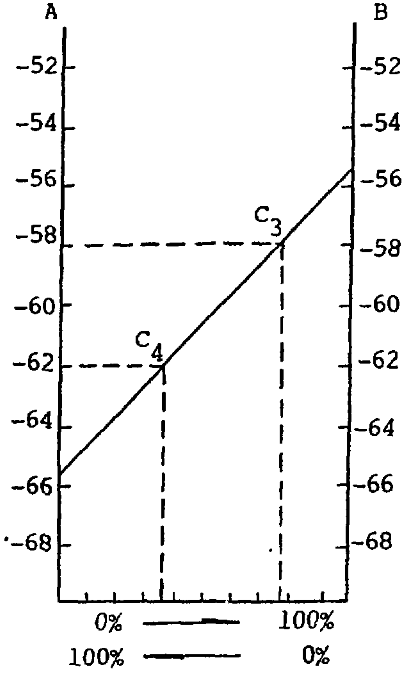


Fig. 5-2 Mixing diagram used for estimating the percentage alluvium water in mixing water

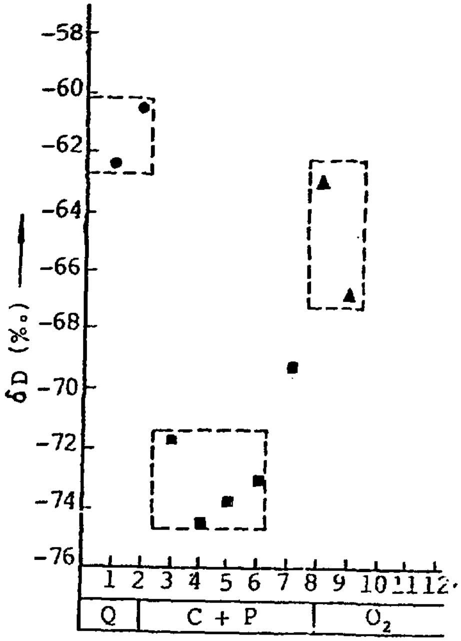
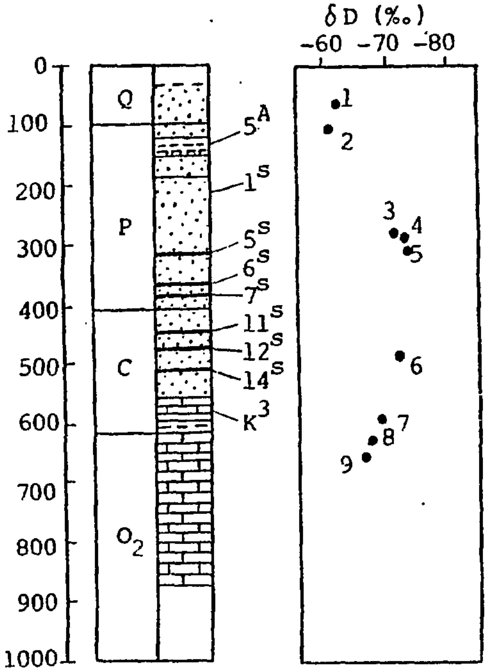
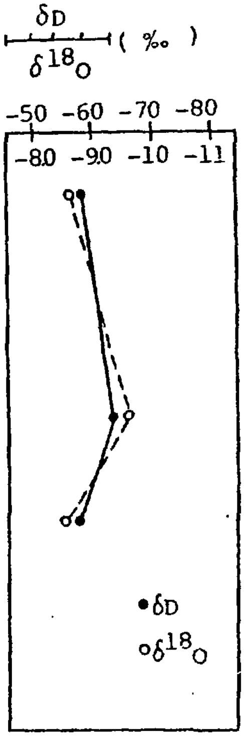


Fig. 6-1 The distribution chart for δD in groundwater from Lin Mancang Coal Mine



6 - 1a

Fig. 6-1a Depth versus δD, Lin Nancang Coal Mine



7 - 1

Fig. 7-1 Depth versus the average $\delta^{18}O$ and δD, the whole study area in Kai Luan Coal Mine