

Issue 4
Volume 1
December, 2024

ISSN 2818-0313
DOI Prefix : 10.62252

Naturalis



Scientias

www.naturalisscientias.com



TABLE OF CONTENTS

Original Articles

A new binary number system for real numbers.....286

Geology and genetic types of the primary rhenium deposits in Mainland
China303

The past, present and future of printing technology - Preface to the
monograph titled Standards and Energy Saving in Printing Ink Curing and
Drying Processes.....324

Type and metallogenic series of the cobalt deposits in the East Kunlun,
China328

Book Review

Finally, the complete eight-volume Collected Works of Chia Yung Hsieh is
published345



Original Article

A new binary number system for real numbers

Deliang Shi ¹

Abstract

A number system uses a set of digits and sign to represent all the numbers. Different number systems use different amount of digits and sign. To compare the leanness of a number system, the cardinality of the complete set of digits and sign are employed in this work. The 01 binary number system is used by almost all the modern computers. It can represent all the real numbers by two digits 0, 1 and a sign (-), which means its cardinality is 3. Thus, the 01 binary system is not a true binary system. After reviewing all the existing number systems it is found that no true binary system exists for real numbers. All the current binary number systems either don't have radix 2, or have cardinality 3. In this paper, a true binary system for real numbers, with both radix and cardinality 2, is invented based on the principle of Yin-Yang. Surprisingly, this binary system can not only represent all real numbers without using a sign, but also perform arithmetic and Boolean operations without any problem. Furthermore, due to its radix being 2, this true binary system is compatible with the 01 binary system and many operations are interchangeable between the two systems. It is expected that this true binary system will be applied in the fields of number representation, computer science and cryptography.

Key words: Binary number system; Cardinality; Yin-Yang; Real numbers

Affiliation Info: ¹Independent Researcher, Vernon Hills, IL 60061, U.S.A.

Author's Contact Info: Shi, DL: deliangshi@gmail.com

Citation: Deliang Shi. 2024. A new binary number system for real numbers. *Naturalis Scientias*, 1 (4): 286-302.

DOI: <https://doi.org/10.62252/NSS.2024.1020>.

Copyright © 2024 by the author. Published by *Naturalis Scientias*. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License. (<https://creativecommons.org/licenses/by-nc/4.0/>).

Corresponding Author : DL Shi, PhD; Email: deliangshi@gmail.com

1. Introduction

There are many different positional number systems. The conventional decimal number system uses 10 digits 0,1...9 to represent numbers and a sign to indicate if it is positive or negative, such as,

$$-987.12 = -(9 \times 10^2 + 8 \times 10^1 + 7 \times 10^0 + 1 \times 10^{-1} + 2 \times 10^{-2}).$$

The 01 binary system is a base-2 system. It can represent every real number using 2 digits and a sign. This system is widely used in the modern computer science¹⁻⁶, such as,

$$-(110.01)_2 = -(1 \times 2^2 + 1 \times 2^1 + 0 \times 2^0 + 0 \times 2^{-1} + 1 \times 2^{-2}).$$

The sign has caused huge complexity on representing numbers in the modern computer system, since the modern computer system relies on two-stage, on and off, to represent all the number. In order to represent both positive and negative numbers, several methods have been used, such as signed magnitude, two's complement, one's complement notations etc. Unfortunately, each method has its own advantages and disadvantages⁷.

There are some number systems that don't need sign inherently, as illustrated in below generalized numeral system.

A generalized numeral system in base b can be expressed as

$$(\dots a_2 a_1 a_0 \cdot a_{-1} a_{-2} \dots)_b = a_2 \times b^2 + a_1 \times b^1 + a_0 \times b^0 + a_{-1} \times b^{-1} + a_{-2} \times b^{-2},$$

where b can be integers, non-integers, positive numbers, negative numbers, irrational numbers and complex numbers etc. In the generalized numeral system, the sign is not required for every number system, since both positive and negative numbers can be represented without sign in a negative based system, such as,

$$(1011)_{-2} = 1 \times (-2)^3 + 0 \times (-2)^2 + 1 \times (-2)^1 + 1 \times (-2)^0 = -9.$$

The complex-base number systems don't need sign as well due to that negative number can be obtained by the multiplication of imaginary numbers. A "binary" complex system based on $\pm\sqrt{2}i$ can represent every complex number using only 0 and 1⁸. Another "binary" complex number system based on $i - 1$ can also represent every complex number using only 0 and 1⁹⁻¹⁰, such as,

$$(101)_{i-1} = 1 \times (i - 1)^2 + 0 \times (i - 1)^1 + 1 \times (i - 1)^0 = 1 - 2i,$$

Unfortunately, both the negative and complex based number systems are not based on positive integers, thus, their applications are very limited.

The balanced ternary system is a base-3 system. It can represent every real number using $-1, 0, 1$ without a sign and some early computers were developed based on this system¹¹. The balanced binary system is a base-2 system. It can represent every real number using $-1, 0, 1$ without a sign¹²⁻¹³. The drawback of these two balanced number systems is that they still need 3 symbols to represent real numbers, which is the same amount as the 0, 1 and sign binary system.

In summary, a lot of efforts have been put on getting a positive integer based system without sign. However, to represent real numbers, all the existing positive integer based systems need use at least 3 symbols, which doesn't match the two-stage of a computer system. There are some negative and complex based number system that can represent all numbers using 2 symbols, but their radices are not 2 and they are not convenient on general usage. Thus, there exists no true binary system for real numbers.

In this work, a true binary system that can represent real numbers using just two symbols without sign will be demonstrated.

2. Cardinality of a positional number system

A positional number system is represented as

$$\langle \rho, Z \rangle$$

with radix ρ and set of digits Z , possibly with a sign \pm ¹⁴. For example, the common 01 binary system has

$$\rho = 2$$

and

$$Z = \{0,1\}.$$

It is represented as

$$\langle 2, \{0,1\} \rangle.$$

Obviously, without the sign, $\langle 2, \{0,1\} \rangle$ can only represent non-negative numbers, i.e.

$$\langle 2, \{0,1\} \rangle \text{ for any } x \in R_+,$$

where R represents the domain for real numbers and R_+ represents the domain for non-negative real numbers.

To represent all real numbers, the sign is required. Here we define Z_c as the complete set of symbols of a numeral system, which include the necessary sign as well.

$$Z_c = \begin{cases} Z & \text{if the system doesn't need sign;} \\ Z \cup \{\pm\} & \text{if the system need sign.} \end{cases}$$

Thus, the positional number system pair becomes

$$\langle \rho, Z_c \rangle.$$

In above notation, there is no need to say if the system need a sign or not, since Z_c is the complete set of all symbols.

Here, we define the cardinality of a positional number system to be the number of elements in set Z_c , i.e.,

$$\text{card}(\langle \rho, Z_c \rangle) = |Z_c|.$$

For binary numeral system representing non-negative numbers , we have

$$Z_c = Z = \{0,1\}.$$

For binary numeral system representing real numbers, we have

$$Z_c = Z \cup \{\pm\} = \{0,1, \pm\}.$$

Thus, we have

$$\langle 2, \{0,1, \pm\} \rangle \text{ for any } x \in R.$$

In above notation, the number system and its domain have been shown together, i.e. in below general form,

$$\langle \rho, Z_c \rangle \text{ for any } x \in D .$$

Since a number system is always related to a domain, we will use above notation to clearly show a number system and its domain.

The cardinality of a number system can be calculated, such as

$$|Z_c| = |\{0,1, \pm\}| = 3,$$

i.e. there are 3 symbols in the number system $\langle 2, \{0,1, \pm\} \rangle$ for any $x \in R$.

Similarly, the balanced binary system can be represented as

$$\langle 2, \{-1, 0, 1\} \rangle \text{ for any } x \in R.$$

We have

$$|Z_c| = |\{-1,0,1\}| = 3,$$

i.e. there are 3 symbols in the number system $\langle 2, \{-1, 0, 1\} \rangle$ for any $x \in R$.

The cardinality of a positional number system can be used to compare different number systems.

The smaller the cardinality, the leaner the system. For any $x \in D$, if there are two number systems $\langle \rho_1, Z_{c1} \rangle$ and $\langle \rho_2, Z_{c2} \rangle$, we can compare them as below,

$$\text{if } |Z_{c1}| = |Z_{c2}| , \text{ then } \langle \rho_1, Z_{c1} \rangle \text{ is as lean as } \langle \rho_2, Z_{c2} \rangle;$$

$$\text{if } |Z_{c1}| < |Z_{c2}| , \text{ then } \langle \rho_1, Z_{c1} \rangle \text{ is leaner than } \langle \rho_2, Z_{c2} \rangle.$$

If a number system has cardinality $|Z_c|$, it is possible to get a new number system which has a bigger cardinality than $|Z_c|$ for that domain by adding some redundancy into the new number system. Though, it is not always true vice versa, since it is not always possible to make a number system leaner if that number system is already the leanest one in the field. Thus, finding the leanest system for a specific field is critical to obtain other possible number systems.

It is easy to see number systems

$$\langle 2, \{0,1, \pm\} \rangle \text{ for any } x \in R$$

and

$$\langle 2, \{-1, 0, 1\} \rangle \text{ for any } x \in R$$

are applied in the same field, i.e. $x \in R$ and they have the same value of $|Z_c|$, i.e. 3. Thus, these two numeral systems are as lean as each other.

It is not hard to check and find that, for $\in R$, all the existing positive integer based number systems having $|Z_c| \geq 3$.

The concept of cardinality can be applied to the computer system as well, since Z_c is defined as the complete set of symbols, not only digits. The cardinality of the computer system can be calculated as,

$$|Z_c| = |\{on, off\}| = 2.$$

Thus, we can clearly see that the gap between the existing binary system and the computer system. The computer system is true binary, since it has only 2 symbols though the existing binary system has 3 symbols. These two systems are not bijective. To close this gap, there are two possible routes.

Route 1: Bring up the $|Z_c|$ of the computer system to 3, to match the number system. There are mainly 3 solutions in this route.

- 1) Use a 3-state computer such as

$$Z_c = \{\text{off, low, high}\}$$

or

$$Z_c = \{\text{negative, off, positive}\}$$

- 2) Define an extra sign bit

$$Z_c = \{\text{on, off, sign}\}.$$

- 3) Use the combination of on and off to form 3 symbols such as in the redundancy binary representation¹⁵⁻¹⁶, i.e. ,

$$Z_c = \{\text{on} - \text{on}, \text{on} - \text{off}, \text{off} - \text{off}\}.$$

It is not hard to see that Route 1 is making the whole system more complicated. Unfortunately, most of the existing solutions are taking this route.

Route 2: Find a new binary number system $\langle 2, Z_c \rangle$ for any $x \in R$ with $|Z_c| = 2$, to match the computer system.

Obviously, Route 2 is reducing the cardinality to simplify the system. So, it is more preferred than route 1. The challenge is that a new binary system need be found and work well, if this new binary system ever exists.

In this work, I will take Route 2 to close the gap. I will use a new way to obtain a true binary system which meet below requirements,

$$\langle 2, Z_c \rangle \text{ for any } x \in R \text{ with } |Z_c| = 2.$$

Obviously, this true binary system will become the leanest base-2 binary system for real numbers. In the end of this work, you will understand why the traditional well-established number system theories don't really help here. Sometimes they are even misleading on finding this true binary number system, such as it is mentioned that there are only two systems of binary coding, namely $\langle 2, \{0, 1\} \rangle$ and $\langle -2, \{0, 1\} \rangle$ ¹⁴.

Before moving forward, let's jump out of the box for the time being and goes back to the origin of the modern binary number system.

3. Binary and Yin-Yang

The modern binary numeral system was invented by Gottfried Wilhelm Leibniz¹⁷. In his work, Leibniz noticed the similarity between Yin-Yang and the 01 binary system¹⁷⁻¹⁸. In the Yin-Yang And Eight Trigrams Graph, Yin is represented as a broken line - - and Yang is represented as a whole line —. Combinations of Yin and Yang comprise the Eight Trigrams ☰, ☷, ☱, ☲, ☴, ☵, ☶, ☳.

Replacing Yin with 0 and Yang with 1, Leibniz noticed that the eight trigrams will become 000, 001, 010, 011, 100, 101, 110, 111, as shown in Figure 1.

☰	000	0	0
☷	001	1	1
☱	010	10	2
☲	011	11	3
☴	100	100	4
☵	101	101	5
☶	110	110	6
☳	111	111	7

Figure 1. The similarity between the 01 binary and Yin-Yang noticed by Leibniz¹⁷

4. Yin-Yang binary number system

After reviewing Leibniz's work, one has to point out that, even if the 01 binary system is similar to Yin-Yang, the 01 representation cannot reflect the true meaning of Yin-Yang. In Yin-Yang theory, Yin means negative and Yang means positive¹⁹⁻²⁴. Yin and Yang are equal but opposite. They are complementary to each other and can make up everything without resorting to a third



party. Using 0 to represent Yin cannot show that Yin is opposite to Yang. In fact, 0 represents neutral instead of negative. Based on the Yin-Yang theory, it is better to use -1 and 1 to represent Yin and Yang than to use 0 and 1.

Thus, a true binary system, using -1 and 1 as the digits, is invented in this work, i.e.

$$\langle 2, \{-1, 1\} \rangle \text{ for any } x \in R.$$

Surprisingly, this binary system works very well on number representation, as will be demonstrated in this work.

Since this true binary system is based on the principle of Yin-Yang, we will call it Yin-Yang binary system in this work. We will use $\bar{1}$ to represent -1, thus we have

$$Yin = -1 = \bar{1},$$

and

$$Yang = 1.$$

The Yin-Yang binary system will be shown as

$$\langle 2, \{\bar{1}, 1\} \rangle \text{ for any } x \in R.$$

The decimal value of a number in Yin-Yang binary system can be calculated, such as,

$$\bar{1}\bar{1} = (-1) \times 2^1 + (-1) \times 2^0 = -2 - 1 = -3.$$

It is obvious that -3 is negative and it has been represented in the Yin-Yang binary system without using the negative sign.

The decimal value of a fraction number can be calculated as well, such as,

$$11.\bar{1}1 = 1 \times 2^1 + 1 \times 2^0 + (-1) \times 2^{-1} + 1 \times 2^{-2} = 2 + 1 - 0.5 + 0.25 = 2.75.$$

A repeating number can also be calculated, such as,

$$.\dot{1} = .111 \dots = 1 \times 2^{-1} + 1 \times 2^{-2} + 1 \times 2^{-3} + \dots = \sum_{n=1}^{\infty} \frac{1}{2^n} = 1,$$

where the dot ($\dot{\cdot}$) above the number indicates a repeating number.

Similarly, we can calculate that below numbers are all equal to 0. Thus, 0 can be represented in the Yin-Yang binary system even though it is not included in the basic digits,

$$\bar{1}.\dot{1} = 1.\dot{\bar{1}} = \bar{1}\dot{1} = .1\dot{\bar{1}} = 0.$$

It is different from other non-zero positional number systems, such as in the bijective base systems, an empty string is used to represent 0²⁵.

A real number x in decimal can be converted to y in the new Yin-Yang binary system by following below procedure.

$$\text{If } x < 0, y = -1.$$

$$\text{Otherwise, } y = 1.$$

$$p = \text{floor}(\log_2|x|).$$

$$x = x - 2^p.$$

Then, repeat below process until accuracy is met.

$$\text{If } x < 0, y = -1.$$

$$\text{Otherwise, } y = 1.$$

$$p = p - 1.$$

$$x = x - 2^p.$$

The sequence of y gotten from this procedure will be the digits in the Yin-Yang binary system. Table 1 shows an example of converting the decimal number 99 to Yin-Yang binary.

Table 1. Conversion of number in decimal to Yin-Yang binary

X	Y	$\log_2 x $	position	2^{position}	$x - y \times 2^{\text{position}}$
99	1	6.4	6	$2^6 = 64$	35
35	1		5	$2^5 = 32$	3
3	1		4	$2^4 = 16$	-13
-13	-1		3	$2^3 = 8$	-5
-5	-1		2	$2^2 = 4$	-1
-1	-1		1	$2^1 = 2$	1
1	1		0	$2^0 = 1$	0

Based on the column of y , 99 in decimal is converted to $111\bar{1}\bar{1}\bar{1}1$ in the Yin-Yang binary system.

Please refer to the Supplement Information for a code written in C language that can convert any real number to Yin-Yang binary. Some typical numbers represented in different numeral systems are shown in Table 2.

Table 2. Some typical numbers represented in different numeral systems

<u>Decimal</u> Need 11 symbols (0,1,2...9 and -) to represent all the real numbers	<u>01 Binary</u> Need 3 symbols (0,1 and -) to represent all the real numbers	<u>Yin-Yang Binary</u> Need only 2 symbols ($\bar{1}$ and 1) or (-1 and 1) to represent all the real numbers
0	0	$\bar{1}. \dot{1}$
1	1	1
2	10	$11. \dot{\bar{1}}$
3	11	11
4	100	$11. \dot{1}$
5	101	$11\bar{1}$
6	110	$111. \dot{\bar{1}}$
7	111	111
8	1000	$1\bar{1}11. \dot{1}$
9	1001	$11\bar{1}\bar{1}$
10	1010	$11\bar{1}1. \dot{\bar{1}}$
-1	-1	$\bar{1}$
-2	-10	$\bar{1}\bar{1}. \dot{1}$
-3	-11	$\bar{1}\bar{1}$
-4	-100	$\bar{1}\bar{1}. \dot{\bar{1}}$
-5	-101	$\bar{1}\bar{1}1$
-6	-110	$\bar{1}\bar{1}\bar{1}. \dot{1}$
-7	-111	$\bar{1}\bar{1}\bar{1}$
-8	-1000	$\bar{1}\bar{1}\bar{1}. \dot{\bar{1}}$



The Yin-Yang binary numbers can perform all the arithmetic operations. It is easy to see below addition operations are valid.

$$1 + 1 = 1.\dot{1}$$

$$\bar{1} + \bar{1} = \bar{1}.\dot{\bar{1}}$$

$$1 + \bar{1} = 1.\dot{\bar{1}}$$

$$1 + 1 + 1 = 11$$

$$\bar{1} + \bar{1} + \bar{1} = \bar{1}\bar{1}$$

$$1 + 1 + \bar{1} = 1$$

$$1 + \bar{1} + \bar{1} = \bar{1}$$

From above addition operations, we can find the addition of 2 digits in Yin-Yang binary will still yield 2 digits. But, the addition of 3 digits will yield only 1 or 2 digits. Thus, as a thumb of rule, we will change the addition of 2 digits into the addition of 1 or 3 digits, by employing the expandability, as exemplified in Table 3.

Since subtraction is inverse to addition, multiplication is repeated addition, and division is inverse to multiplication, we can expect these operations will be successfully performed if the addition operation can be successfully performed.

The three basic subtractions are:

$$\bar{1} - \bar{1} = \bar{1} + 1 = \bar{1}.\dot{1}$$

$$1 - 1 = 1 + \bar{1} = \bar{1}.\dot{1}$$

$$1 - \bar{1} = 1 + 1 = 1.\dot{1}$$

The three basic multiplication operations are:

$$1 \times 1 = 1$$

$$\bar{1} \times \bar{1} = 1$$

$$1 \times \bar{1} = \bar{1}$$

The three basic division operations are:

$$1/1 = 1$$

$$\bar{1}/1 = \bar{1}$$

$$1/\bar{1} = \bar{1}$$

Examples of general arithmetic operations are shown in Table 3.

Table 3. Addition, subtraction, multiplication and division operations in Yin-Yang binary

Addition	Subtraction	Multiplication	Division
$\begin{array}{r} \bar{1} \bar{1} 1 \\ + \quad 1 1 \\ \hline \bar{1} \bar{1} 1 . \dot{1} \\ + \quad 1 \\ \hline \bar{1} \bar{1} \bar{1} . \dot{1} \\ \quad 1 \\ + \quad 1 \\ \hline \bar{1} 1 \bar{1} . \dot{1} \\ \hline \bar{1} \bar{1} . \dot{1} \end{array} \begin{array}{l} -5 \\ 3 \\ -2 \\ -2 \end{array}$	$\begin{array}{r} \bar{1} \bar{1} 1 \\ - \quad 1 1 \\ \hline \bar{1} \bar{1} 1 . \dot{\bar{1}} \\ - \quad 1 \\ \hline \bar{1} \bar{1} \bar{1} . \dot{\bar{1}} \\ \quad 1 \\ - \quad 1 \\ \hline \bar{1} \bar{1} \bar{1} . \dot{\bar{1}} \end{array} \begin{array}{l} -5 \\ 3 \\ -8 \end{array}$	$\begin{array}{r} \bar{1} \bar{1} 1 \\ \times \quad 1 1 \\ \hline \bar{1} \bar{1} 1 \\ + \bar{1} \bar{1} 1 \\ \hline \bar{1} \bar{1} \bar{1} \\ \bar{1} \bar{1} 1 \\ + \quad 1 \\ \hline \bar{1} 1 \bar{1} \\ + \bar{1} \bar{1} \\ \hline \bar{1} \bar{1} \bar{1} \\ \bar{1} \bar{1} \\ + \quad 1 \\ \hline \bar{1} \bar{1} \bar{1} \bar{1} \end{array} \begin{array}{l} -5 \\ 3 \\ -15 \end{array}$	$\begin{array}{r} \bar{1} 1 \\ 3 \parallel 1 1 \overline{) \bar{1} \bar{1} 1} \\ \underline{- \bar{1} \bar{1}} \\ 1 \\ \underline{- 1 1} \\ \bar{1} 1 . \dot{\bar{1}} \end{array} \begin{array}{l} -1 \\ -5 \\ -2 \end{array}$

The operations are illustrated by $-5+3$, $-5-3$, -5×3 and $-5/3$.

7. Boolean operations

Boolean operations can also be performed in Yin-Yang binary. There are 3 basic Boolean operations, i.e. AND, OR and NOT. More complicated Boolean algebra can be achieved by combing these three basic Boolean operations²⁶.

AND is defined as $X \text{ AND } Y=1$ if $X=Y=1$, otherwise $X \text{ AND } Y=\bar{1}$.

Here, $X \text{ AND } Y$ is similar to minimum operation, i.e., $X \text{ AND } Y = \min(X, Y)$.

OR is defined as $X \text{ OR } Y=\bar{1}$ if $X=Y=\bar{1}$, otherwise $X \text{ OR } Y=1$.

Here, $X \text{ OR } Y$ is similar to the maximum operation, i.e. $X \text{ OR } Y = \max(X, Y)$

NOT is defined as $\text{NOT } X=\bar{1}$ if $X=1$ and $\text{NOT } X=1$ if $X=\bar{1}$.

Here, $\text{NOT } X$ is similar to the negative operation, i.e. $-X$.

We can see the AND and OR operations are similar to those in 01 binary system. The NOT operation is the negative operation and it is more instinct than that in 01 binary system. The Truth Table is summarized in Table 4.

Table 4. The Truth Table in Yin-Yang binary

X	Y	X and Y	X or Y
$\bar{1}$	$\bar{1}$	$\bar{1}$	$\bar{1}$
1	$\bar{1}$	$\bar{1}$	1
$\bar{1}$	1	$\bar{1}$	1
1	1	1	1

X	not X
$\bar{1}$	1
1	$\bar{1}$

It is noted that the Boolean Operations in Yin-Yang binary can be easily converted to Zadeh Operation for Fuzzy logic²⁷⁻²⁸, except that the Not operation should also be the Negative Operation, as shown in Table 5.

Table 5. Fuzzy logic operations in Yin-Yang binary.

Boolean Operations	Fuzzy Logic Operations
X AND Y	$\min(X, Y)$
X OR Y	$\max(X, Y)$
NOT X	$-X$

8. Discussion

So far, we have obtained a true binary number system which meets the requirement

$$\langle 2, Z_c \rangle \text{ for any } x \in R \text{ with } |Z_c| = 2,$$

i.e., the Yin-Yang binary system

$$\langle 2, \{\bar{1}, 1\} \rangle = \langle 2, \{-1, 1\} \rangle \text{ for any } x \in R.$$

This number system can represent every real number without sign. Furthermore, it can perform all the arithmetic and Boolean operations easily. Besides that, it also has below advantages:

- 1) The negative of a number can be obtained by exchanging 1 and -1.
- 2) The sign of a number is given by its most significant digit, except 0, which can be either positive or negative.

- 3) Since the system is based on 2, it is compatible with the current 01 binary system when performing arithmetic operations. Thus, many operations could be performed seamlessly between the two systems, as shown in Table 6.

Table 6. Arithmetic operations between Yin-Yang Binary and 01 binary are compatible

	1̄	1		Yin-Yang Binary
+	1	0		01 Binary
		1		Result

The disadvantage of this number system is that it need use infinite repeating fraction to represent even integers. But, as most of real numbers are approximated in the 01 binary system, the accuracy of any number in the Yin-Yang binary system can be represented accurate enough and it is only limited to the capacity of the computer.

Here let's discuss why this true binary number system can only be obtained by a non-traditional way. In traditional theories of number systems, there are many stereotypes, such as most number systems include 0 in the system, or the digits are continuous integers. For example, the digits of a balanced number system base- b is generalized as²⁹,

$$-k \text{ to } (b - 1) - k \text{ where } k = \left\lfloor \frac{b}{2} \right\rfloor.$$

We can see, as a balanced number system, Yin-Yang binary system doesn't follow above generalized rule. Thus, it may explain why it was not found before.

As a true binary system for representing real number, Yin-Yang binary system have a lot of potential applications. In many cases there are only two symbols available, such as a coin having only two sides, a magnet having only two poles and a black white printer can only show two colors. Thus, using only 2 symbols to represent as much information as possible is often not only preferred, but also required³⁰⁻³¹. Yin-Yang binary system provides the mathematical foundation for using only 2 symbols in a base-2 system to represent all real numbers, which has never been achieved before by any other number systems.

9. Conclusions

The cardinality of the complete set of digits and sign is defined in this work to compare the leanness of different number systems. It is found that the existing binary systems all having cardinality 3, thus they are not true binary systems.

A true binary number system based on the principle of Yin-Yang is introduced in this work. Comparing to the existing binary systems, Yin-Yang binary system has cardinality 2 and uses only 2 symbols, thus it is a true binary system. It can not only represent all real numbers, but also perform arithmetic and Boolean operations without any problem.



10. References

1. Randell B. 1982. From analytical engine to electronic digital computer: the contributions of Ludgate, Torres, and Bush. *IEEE Ann. Hist. Comput.*, 4 (4) : 327–341.
2. Zuse K. 1993. *The Computer - My Life*. Springer Science & Business Media, Berlin .
3. Rojas R. 1997. Konrad Zuse's Legacy: The Architecture of the Z1 and Z3. *IEEE Ann. Hist. Comput.*, 19 (2): 5–15.
4. Copeland B. 2017. “The modern history of computing” in the *Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University.
5. Shannon C. & Weaver W. 1949. *The Mathematical Theory of Communication*. University of Illinois Press.
6. Stokes J. 2007. *Inside the machine: an illustrated introduction to microprocessors and computer architecture*. No Starch Press, San Francisco.
7. Knuth D. 1997. “Seminumerical Algorithms” in the *Art of Computer Programming*. Addison-Wesley, 2.
8. Knuth D. 1960. An imaginary number system. *Commun. ACM.*, 3 (4): 245–247.
9. Khmelnik S. 1962. “A Specialized Computer for Operations on Complex Numbers” in *Questions of Radio Electronics XII*, No. 2.
10. Penney W. 1965. A "binary" system for complex numbers. *JACM.*, 2 (12): 247-248.
11. Glusker D, Hogan P & Vass. 2005. The ternary calculating machine of Thomas fowler. *IEEE Ann. Hist. Comput.*, 3 (27): 4–22.
12. Reitwiesner G. 1960. Binary arithmetic. *Adv. in Compu.*, 1: 231-308.
13. Knuth D. 1986. Efficient balanced codes. *IEEE Trans. Inf. Theory.*, 1 (32): 51–53.
14. Khmelnik S & Doubson I. 2011. Positional codes of complex numbers and vectors. *Mathematics in Computers Corp.*, Israel.
15. Lapointe M, Huynh H & Fortier P. 1993. Systematic design of pipelined recursive filters. *IEEE Trans Comput.*, 4 (42): 413–426.
16. Phatak D & Koren I. 1994. Hybrid signed-digit number systems: A unified framework for redundant number representations with bounded carry propagation chains. *IEEE Trans Comput.*, 8 (43): 880–891.
17. Leibniz G. 1879. Explanation of binary arithmetic, which uses only the characters 1 and 0, with some remarks on its usefulness, and on the light it throws on the ancient Chinese figures of Fu Xi. *Mathematical Writings VII*. ed. C. Gerhardt, Berlin, 7: 223.
18. Ryan J. 1996. Leibniz' binary system and Shao Yong's "Yijing". *Philos. East West.*, 1 (46): 59–90.
19. Wang H. (Ed.). 2011. *I Ching*. Yunnan People's Publishing House, Kunming.
20. Richard W, Baynes C & Brown J. 1977. *The I Ching or Book of Changes*. Princeton University Press.
21. Needham J. 1956. Science and civilization in China. 2: *History of Scientific Thought*. Cambridge University Press.
22. Zhang W, Pandurangi A & Peace K. 2007. Yin Yang dynamic neurobiological modeling and diagnostic analysis of major depressive and bipolar disorders. *IEEE Trans. Biomed. Eng.*, 10 (54): 1729-1739.
23. Hahn S. 1992. The Yin and the Yang of mammalian transcription. *Curr. Biol.*, 3 (2): 152-154.
24. Gore J & Oudenaarden A. 2009. The yin and yang of nature. *Nature*, 457: 271–272.
25. Foster J. 1947. A number system without a zero symbol, *Mathematics Magazine*, 1 (21): 39-41.
26. Givant S & Halmos P. 2009. *Introduction to Boolean Algebras*. Springer, New York.



27. Zadeh L. 1965. Fuzzy sets. *Information and Control*, 3 (8): 338-353.
28. Novak V, Perfilieva I & Mockor J. 1999. *Mathematical Principles of Fuzzy Logic*. Springer US.
29. Parhami B. 1988. Carry-free addition of recoded binary signed-digit numbers. *IEEE Trans. Comput.*, 11 (37): 1470-1476.
30. Hankerson D, Menezes A & Vanstone S. 2004. *Guide to Elliptic Curve Cryptography*. Springer-Verlag, New York.
31. Querini M, Grillo A, Lentini A & Italiano G. 2011. 2D color barcodes for mobile phones. *Int. J. Compu. Sci. App.*, 1 (8): 136-155.

Acknowledgements

I want to thank F.T. Shi for teaching me the knowledge of Yin-Yang. I want to thank Dr. X. Fan for reviewing the initial manuscript.

Data availability

The data that support the findings of this study is available from the author upon reasonable request.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI tools declaration

The author declares that he has not used Artificial Intelligence (AI) tools in the creation of this article.

Appendix:

Below is a code written in C language that can convert any real number to the Yin-Yang binary number system.

```
/****** convert_decimal_to_yinyang.c *****/
#include <stdio.h>
#include <math.h>

float x; /*Any real number*/
int y; /*Yin-Yang binary*/
int p; /*Digit position in Yin-Yang binary */

int main() {
    printf("Please input any real number, then press carriage return.\n");
    scanf("%f",&x);
    printf("\n%f in decimal is \n", x);

    y=1;
```



```
if(x<0) y=-1;
p=floor(log2(fabs(x)));
if(fabs(x)<1) {
    printf(". ");
    p=-1;
}
printf("%d ",y);

while(p>-10){
    x=x-y*pow(2,p);
    if(p==0) {
        if(fabs(x)<1e-6) break;
        printf(". ");
    }
    y=1;
    if(x<0) y=-1;
    printf("%d ",y);
    p=p-1;
}
printf("\nin Yin-Yang binary.\n");
return 0;
}
/*****End of the Code*****/
```





Original Article

Geology and genetic types of the primary rhenium deposits in Mainland China

Jian Zhao Yin ^{1,2,3}

Abstract

The unique physical and chemical properties of the rare element rhenium make it have increasingly extensive and indispensable uses in many modern high-tech fields such as national defense, aerospace, petrochemical industry, electronic materials, quantum computing and ultra-high temperature emitters, and medicine. For this reason, many countries, especially Western developed countries, have listed rhenium as one of the critical metals or strategic minerals for protection and restriction. Due to the heterogeneity of the distribution of chemical elements throughout the earth, compared with similar minerals in other continents, the rhenium deposits in mainland China have both similarities and unique features. For example, mainland China has the only independent rhenium deposit in the world so far. At the same time, mainland China also has associated and/or symbiotic rhenium ore types that most countries in the world have. China's large-scale rhenium exploration, research and application started late. But it has developed rapidly in the past 10-20 years. This article summarizes the geological characteristics of the rhenium deposits discovered in mainland China in recent times and divides their genetic and industrial types.

Key words: rhenium deposit; mainland China; application; market; geology; genetic type

Affiliation Info: ¹ Orient Resources Ltd., Canada; ² Wuhan Institute of Technology, Wuhan 430205, China; ³ College of Earth Sciences, Jilin University, Changchun 130061, China

Authors' Contact Info: Yin, JZ: jzyin7@jlu.edu.cn

Citation: JZ Yin. 2024. Geology and genetic types of the primary rhenium deposits in Mainland China. *Naturalis Scientias*, 1 (4): 303-323. DOI: <https://doi.org/10.62252/NSS.2024.1021>. www.naturalisscientias.com

Copyright © 2024 by the author. Published by *Naturalis Scientias*. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License. (<https://creativecommons.org/licenses/by-nc/4.0/>).

Corresponding Author : Yin, JZ, PhD, PGeo, Professor; Email: jzyin7@jlu.edu.cn

1. Introduction

As early as 1871, the founder of the periodic table, Russian chemist Dmitri Mendeleev, brilliantly predicted that there was a "manganese-like" element with an atomic weight of 190 in nature. In 1913, the British genius physicist Henry Moseley further predicted the new elements 43, 61, 72 and 75 that had not yet been discovered in the periodic table at that time, among which 75 was Re that was later discovered. In 1925, German chemists Walter Noddack, Ida Tacke and Otto Berg used X-rays to discover the belated element 75 in platinum ore and columbite, and named the newly discovered element Rhenium after the Rhine River, where Ada was born. Rhenium thus became the last natural element discovered in the periodic table. In 1928, German scientist Nordak separated and obtained the first 1 g of rhenium metal in human history from 660 kg of molybdenite in the laboratory¹⁻³. However, the large-scale production of rhenium began two years later in 1930.

Rhenium, a rare metal that has long been unknown to the world, has rapidly attracted widespread attention in the past 20-30 years due to the highly developed modern science and technology and its wide application in many high-tech fields. Many countries have even listed it as a critical metal for protection.

2. Chemical and physical properties, uses, production and market of rhenium

2.1 Chemical and physical properties

As a highly dispersed and therefore extremely rare element, rhenium has an abundance of only one billionth of an order of magnitude; namely, 10^{-9} in the Earth's crust (Table 1), which is lower than the content of any rare earth element in the periodic table. Re has similar atomic and ionic radii to Mo and Cu, and therefore coexists and thrives with these two metals³⁻⁶. The highly electronegative metallic rhenium crystal belongs to the hexagonal system, with a unit cell edge length a_0 of 2.760 Å and c_0 of 4.458 Å, and is most stable with a 4-valent cation. Therefore, rhenium mainly coexists and/or associates with molybdenite and various copper sulfides, and mostly appears in these minerals in the form of isomorphous impurities. Indeed, rhenium is mainly distributed in countries rich in copper and molybdenum ore resources. Although there are reports that independent rhenium deposits have been discovered in mainland China, most of the Re metal currently used by humans is mainly enriched and separated and purified from by-products such as soot and waste acid from the smelting of Mo and Cu ores.

Table 1. Abundance of rhenium in various rocks from the Earth (modified from Zhou et. al.⁵)

Sample source	$w B/10^{-9}$	
	Range	Average
The Earth's Core		291
Primitive mantle		0.27
Depleted mantle		0.12
Oceanic crust		0.96
Continental crust		2
Ultrabasic rocks (peridotite)	0.003~1.15	
Basic rocks (gabbro, diabase, basalt)	0.36~1.5	
Intermediate rocks (diorite, monzonite, andesite)	< 0.5	
Acidic rocks (such as granite, porphyry, rhyolite)	0.22~1.14	
MORB	0.33~1.47	0.93
OIB	0.1~0.642	0.35
Common shale	9~51	
Black shale	56~285	
Sulfide-rich mineralized black shale	Up to 33,000	
Anoxic sediments	2~127	50
Oxygen-containing sediments	< 0.1	

There are very few known rhenium minerals (Table 2). The first rhenium mineral discovered in the world, dzhezkasganite, comes from the Dzhezkasgan sandstone copper deposit in central Kazakhstan. Later, some rhenium minerals were found in the graphite-rich pyroxene rocks of the Stillwater complex in the United States³⁻⁷. Then, pure rhenium mineral rheniite was found in the Kudriavy crater in the Kuril Islands of the Far East in Russia. This is also the only pure rhenium mineral found in the world so far⁷.

Table 2. Known minerals of rhenium in the world (modified from Zhou et. al.⁵)

Origin	Country	Mineral name	Chemical formula
Zhazgan sandstone Cu deposit	Kazakhstan	Dzjezkazganite	CuReS ₂
Zhazgan sandstone Cu-Mo deposit		-	Cu(Re, Mo)S ₄
Voronov Bor, Rybozero Cu-Mo eposit	Russia	Osmium-cupreous rheniite	(Re, Cu, Os, Fe)S ₂
Sublimates of Kudryavyi volcano; Sugraly sandstone uranium deposit in Uzbekistan; Copper-bearing shale in Mansfeld Cu mine in Germany	Japan, Uzbekistan, Germany	Rheniite	ReS ₂
-	Finland	Tarkianite	(Cu, Fe)(Re, Mo) ₄ S ₈
Danba Yangliuping Cu-Ni deposit	China	-	(Re, Cu, Os, Fe, Ni, Pb)S ₂
	China	-	(Re, Cu, Fe)S ₂
Northern Arizona	USA	Oxided rhenium	Re ₂ O ₇
Transbaikal tungsten deposit	The former USSR	Native rhenium	Re or Re ⁰
Meteorites	-	Ruthenium-rhenium ore	Re ₉₇ Ru ₃
Stillwater ultrabasic intrusion	USA	Rhenium sulfide	Re ₂ S ₃
Coldwell complex in Canada	Canada	-	(Re, Mo, Fe, Cu)S ₃ , Re(Mo, Cu, Fe) ₂ S ₃
	Switzerland or Italy	-	(Pb _{0.87} Si _{0.83} Y _{0.43})(Ti _{14.4} Fe _{6.05} Re _{0.23} Mn _{0.23})O ₃₈
Ni-rich ultrabasic rock in Njuggtraskliden and Caledonian uranium-mineralized quartzite in Solvbacktjam	Sweden	-	Cu(Re ₃ , Mo)S ₈

As one of the few rare metals on the Earth, silvery white rhenium is hard, has high resistivity, is resistant to high temperatures and corrosion, wear and stretch. It has a melting point of 3,180 °C and a boiling point of 5,627 °C. Its melting point ranks third among all elements, only after W and Ta. Its boiling point is the highest among all known metals. The density of rhenium is 21.04 g/cm³, ranking fourth among all metals. Its resistivity is 3.84 times that of tungsten. Its elastic modulus and mechanical properties are close to iron³⁻⁷.

2.2 Use

The unique physical and chemical properties of rhenium make it widely used in defense, aerospace, petrochemical industry, electronic materials including quantum computing, ultra-high temperature emitters, and medicine. For example, it is widely used to make electrodes, thermocouples, high temperature and corrosion resistant alloys, and as a catalyst, etc.²⁻⁷.

When rhenium is added as an additive to alloys such as tungsten, molybdenum and chromium, the strength and plasticity of these metal alloys are significantly improved. Therefore, high-temperature alloys such as rhenium-tungsten, rhenium-molybdenum and rhenium-nickel are widely used in industries such as aerospace and electronics. Ta and W alloys with Re added are the most high-temperature resistant metal alloys known so far. For example, the Re-W thermocouple can measure a high temperature of up to 3,100 °C. The cathode of the electron tube made of Re-W alloy has a lifespan 100 times longer than that of ordinary tungsten electron tubes. The ultra-high temperature emitter material with Re added can increase the discharge effect of hot electrons by 20%. The parts such as aircraft engine turbine blades, combustion chambers and jet nozzles with Re added have greatly improved their deformation resistance and creep resistance under long-term high temperature and high pressure, and extended their service life.



The creep life of nickel-based single crystal high-temperature alloys with 3% to 6% rhenium added is increased by a full 10 times. In a sense, the addition of rhenium determines the service life and quality of one or several generations of single crystal blades, and these blade materials directly determine the service life and quality of one or several generations of engines. This phenomenon is called the "rhenium effect" by scientists. According to statistics, 80% of the world's rhenium is currently used in the aviation engine industry. Rhenium is therefore of great strategic significance in national defense and the military, and is also called "aviation metal", "a super metal", "a strategic metal" or "rocket engine bone strengthening powder"¹⁻⁷.

The first application of rhenium began in the 1960s when Chevron and UOP Inc. jointly invented a rhenium-containing catalyst for oil processing. This rhenium-platinum alloy catalyst not only improved the depth of the reforming reaction, but also increased the productivity of gasoline, aromatics and hydrogen¹⁻⁵. Since then, Re-Pt catalysts have been successfully launched and quickly and widely used in the oil industry, such as the production of lead-free and high-octane gasoline. This has ushered in a new era of "oil purification". Currently, about 90% of chemical products require rhenium and other catalysts. Once rhenium-platinum alloys appeared, they became very popular. The manufacture of high-efficiency catalysts and solar cells cannot be separated from the participation of rhenium. By the early 1970s, between 1978 and 1980, the sharp increase in rhenium demand caused its price to rise by three times. In the 1980s, people found that rhenium-nickel alloys had excellent properties of high temperature resistance, wear resistance and tensile resistance, making them the best choice for the production of single crystal blades for aviation. Rhenium alloy can withstand a weight of 117 tons without deformation. The engine nozzle made of it can withstand 100,000 thermal fatigue cycles, which is very suitable for producing parts for the most complex and harshest parts of aircraft engines. These key parts directly determine the performance and safety of aircraft engines.

In recent years, new biomedical metal materials with Re as an additive have greatly improved medical technology with their excellent performance, and have therefore been widely used in fields such as trauma repair and orthopedics. For example, "heart stent" surgical implants made of advanced medical metal material rhenium-molybdenum alloy still have good plasticity, resistance to physiological corrosion, fatigue resistance and wear resistance at high strength, thus benefiting patients and changing the human world. Rhenium can be seen in the fields of medicine, petrochemicals, and so on: high-speed rotating X-ray tube targets made of rhenium-tungsten alloy, radiopharmaceuticals for treating malignant tumors, long-life grids for microwave communications, heating tubes for space reactor cores, electric filaments for making special incandescent bulbs, shells of artificial satellites and rockets, protective plates for atomic reactors, evaporated metals used as ultra-high temperature heaters, and high-temperature coatings on rockets and missiles, etc.

2.3 Production and market

2.3.1 Global

Since 2011, global rhenium production has been in a state of fluctuation. In 2021, global rhenium production totaled 59 tons, a decrease of 0.3 tons from 2020. Global rhenium deposits are mainly concentrated in the United States, Chile and Poland, with a total production of 47.6 tons in 2021,

accounting for about 80.7% of the global total production. The next rhenium producing countries are Uzbekistan, China, Kazakhstan and Armenia. Chile has the richest rhenium resources, followed by the United States, Russia, Kazakhstan, Armenia, Peru and Canada³⁻⁴. The rhenium resources and reserves in mainland China are relatively small thus far. The estimated rhenium metal pellet price averaged \$1,070 per kilogram in 2023, a 5% decrease from the annual average price in 2022⁸. In 2023, apparent consumption in the United States was about 22% less than that in 2022. During 2023, the United States continued to rely on imports for much of its supply of rhenium. Canada, Chile, Germany, Kazakhstan, and Poland supplied most of the imported rhenium. Imports of APR decreased by an estimated 44% in 2023 compared with those in 2022. Imports of rhenium metal decreased by an estimated 8% in 2023 compared with those in 2022. Estimated world rhenium production in 2023 increased slightly compared with that in 2022.

The United States and Germany continued to be the leading secondary rhenium producers. Secondary rhenium production also took place in Canada, Estonia, France, Japan, Poland, and Russia. Industry sources estimated that approximately 25,000 kilograms of secondary rhenium was produced worldwide in 2023. There were no primary rhenium projects in 2023 that were expected to significantly contribute to rhenium availability in the immediate future⁸.

About 90% of the world's rhenium metal is produced in porphyry deposits. The proven rhenium reserves are about 2,400 tons, mainly distributed in Northern Europe, Central Asia, North America and South America. From the perspective of global metallogenic belts, rhenium-containing deposits are concentrated in the Western Pacific metallogenic belt, the Tethys metallogenic belt, the Central Asia-Mongolia metallogenic belt and the Indian Craton metallogenic area³⁻⁴. Chile, which has 50% of the world's rhenium production, is the world's largest rhenium supplier. Other major producers include the United States and Poland. China's rhenium resources are not rich, with a reserve of 237 tons.

In terms of the development and utilization of rhenium metal, five countries, including the United States, the United Kingdom, France, Canada and Russia, can produce alloy steel containing rhenium.

2.3.2 China

The production of rhenium metal in mainland China has always been low, reaching 5.13 tons in 2021, and a year-on-year increase of 1.8%. The demand is 11.89 tons, a year-on-year increase of 5.64%. However, in terms of primary rhenium ore resources, the country has not yet systematically carried out rhenium resource evaluation and prospecting work, and only obtained some rhenium resources in the process of exploring molybdenum or copper-molybdenum deposits³⁻⁴. The sources of rhenium metal in mainland China include primary rhenium produced from mines and recycled rhenium. In 2021, the production of recycled rhenium metal in mainland China was 2,625 kilograms, accounting for 51.22% of the country's total rhenium production that year. Primary mines produced 2,500 kilograms of rhenium metal, accounting for 48.78%⁹⁻¹⁰.

Affected by the decline in product prices, the market size of the rhenium industry in mainland China has shown a gradual downward trend: the country's rhenium market size was about RMB 488 million in 2014, and it quickly fell to RMB 207 million in 2021. In terms of rhenium metal consumption, the country mainly focuses on the two most important uses, high-temperature



alloys and catalysts. In 2021, the demand for rhenium in the catalyst field in mainland China reached 62%, while the high-temperature assistant alloy field accounted for 14.64%³⁻⁴.

It is worth mentioning that China began to extract rhenium from molybdenum concentrate roasting dust in the 1960s. Generally, molybdenite concentrate contains 0.001%-0.031% rhenium. To extract 1kg of rhenium, it is usually necessary to process 1000-2000 tons of related ores. Obviously, the investment is very huge. At present, there are two main processes for extracting rhenium: wet method and pyrometallurgy. According to some data, the amount of rhenium lost from the waste acid of copper smelting industry in China is 200~500 kg per year^{1,4}, which is an astonishing waste.

Compared with developed countries in the world, the rhenium industry in mainland China is still in its infancy. And its development and utilization are heavily dependent on the development and utilization of host ore deposits, and it will take some time to form a scale. In other words, rhenium ore resources still have a large development space in mainland China.

It is worth mentioning that China began to extract rhenium from molybdenum concentrate roasting dust in the 1960s. Generally, molybdenite concentrate contains 0.001%-0.031% rhenium. To extract 1 kg of rhenium, it is usually necessary to process 1000-2000 tons of related ores. Obviously, the investment is very huge. At present, there are two main processes for extracting rhenium: wet method and pyrometallurgy. According to some data, the amount of rhenium lost from the waste acid of copper smelting industry in China is 200~500 kg per year^{1,4}, which is an astonishing waste.

Compared with developed countries in the world, the rhenium industry in mainland China is still in its infancy. And its development and utilization are heavily dependent on the development and utilization of host ore deposits, and it will take some time to form a scale. In other words, rhenium ore resources still have a large development space in mainland China.

3. Geographical distribution and geology of rhenium deposits in mainland China

3.1 Geographical distribution

In recent years, with the increasing attention paid to strategic emerging minerals, or so-called critical minerals in the West, mainland China has successively discovered considerable natural rhenium resources in the Zhanling molybdenum deposit in Jingxian County, Anhui; the Lala copper deposit in Sichuan; and the Laochang porphyry molybdenum deposit in Lancang, Yunnan (Table 3). In 2008, an independent sandstone rhenium deposit was discovered in Muchuan, Sichuan. Two years later, in 2010, the Huanglongpu molybdenum deposit in Luonan County, Shaanxi was discovered. At that time, it was reported that the “reserves” of associated rhenium ore in the Huanglongpu molybdenum deposit were about 176 tons, accounting for about 7% of the global reserves, second only to Chile, the United States, Russia and Kazakhstan³⁻⁵. It should be pointed out that the so-called “reserves” here should be low-level resources, not real reserves. The news media in mainland China and even scientific research institutions engaged in pure theoretical research often do not understand the huge difference between the terms “resources” and “reserves”. In 2017, 30 tons of associated rhenium was discovered in the Zhanling



molybdenum deposit in Jingxian County, Anhui Province. This number should also be a low-level resource volume, rather than a real reserve in the Western industry.

Table 3. Known paragenetic/associated rhenium deposits in mainland China (modified from Zhou et. al.⁵)

Province (Region)	Deposit	Type	Commodity	Age	Average Mo grade	Min. Re in Moly*	Max. Re in Moly	Average Re in Moly	Total ore	Total Mo metal	Average Re grade	Total Re metal
				Ma	%	10 ⁻⁶			Mt	10,000 tons	g/t	ton
Anhui	Shapinggou	Pohphyry	Mo-Cu	108.1	0.144	2.41	15.7	8.58	1582	245.9	0.012	20
Heilongjiang	Duobaoshan		Cu-Mo	474.5	0.02-0.03	353.9	729.4	492	951	15.22	0.149	142
Hubei	Jiguanzui	Skarn	Cu-Au	138		425.7	1 152	734.9				
	Tonglushan		Cu-Au	137		261.4	665.4	385.7		0.68		3
Inner Mongolia	Bainaimiao	Pohphyry	Cu-Mo-Au	433.95	0.106	134.2	254.3	201.9	11.04	1.17	0.181	2
	Wunugestushan		Cu-Mo	171.6	0.015	215.8	919.8	512.8	435	45	0.077	33
Jilin	Daheishan	Pohphyry	Mo	169	0.081	24.15	42.8	33.7	1045	149.72	0.002	2
Jiangxi	Dexing		Cu	171	0.016	172.3	591.4	358	1825	27.2	0.057	105
	Taqian	Skarn	W-Mo	162		19.17	87.7	43.7		1.59		1
	Tongkengzhang	Pohphyry	Mo	1 347	0.13	1 125	1 338	1 256	1	0.13	1	2
	Xiongjiashan, Jinxi		Mo	155		171.3	614.5	450				
Liaoning	Xiaojiayingzi	Skarn	Mo-Fe	161.4	0.23	21.75	163.1	64.3	8.87	10.05	0.148	1
	Yangjiazhangzi		Mo	189		33.8	53.1	43.5		26.18		11
Shaanxi	Huanglongpu	C - vein	Mo-Pb	222	0.1	71	260	135	120	12	0.133	16
	Jinduicheng	Pohphyry	Mo	138	0.106	4.2	26	14.46	1 089	97.1	0.026	28
	Nannihu-Sandaozhuang	Skarn	W-Mo	144	0.143	9	51	23.33	1 033.6	147.8	0.033	34
Sichuan	Muchuan	Sandstone	Cu-Mo-Re									
Tibet	Chengba	Skarn	Cu-Mo	58.5		84.6	461.3	252	899.1			
	Jiama	Pohphyry	Cu-Mo	14.3		61.66	2 232	185.5		60		111
		Skarn	Pb-Zn									
	Jigongcun	Quartz vein	Mo	22.5	0.13	1410	1 691	1 525	48.8	6.34	3.47	166.3
	Lakange	Pohphyry	Cu	13		343.6	837.5	538				
	Nuri	Skarn	Cu-Mo-W	24.1	0.073	285	605.5	417	134.6	2.86	0.304	41
	Qulong	Pohphyry	Cu-Mo	16	0.032	306	1 218.2	616	1 517	45.7	0.197	299
	Tinggong	Pohphyry	Cu-Mo	16		225.7	922.7	486		1.05		5
Xiongqun	Pohphyry	Cu-Mo-Au	166		1 615	12 182	4 146					
Xinjiang	Donggebi	Pohphyry	Mo	211.7	0.113	6.54	84.2	35.4	350.24	39.6	0.04	14
	Boluokenu	Skarn	Cu-Mo	288.1		54.3	77.8	64.4				
	Xilekuduke	Pohphyry	Cu-Mo	329.2		118	572.1	317				
	Zhajisitan	Sandstone	Re-U									
Yunnan	Pulong	Pohphyry	Cu-Mo-Au	213	0.004	239.8	379.3	318.5	271.93	4.72	0.013	3
	Machangqing	Pohphyry	Cu-Mo-Au	34.6	0.093	34.1	63.9	49.1	58.9	5.48	0.051	3

Note: Moly - Molybdenite; C-vein - Carbonate vein.

One fact is that the rhenium resources in mainland China are still relatively scarce, with low resource and reserves. The reserves of rhenium are less than 300 tons, accounting for only about 7% of the global total⁵. Of course, another fact is that mainland China has made some progress in the exploration, mining and utilization of rhenium in recent years, and the annual output of some rhenium mines is about two tons⁵. As for the currently known production areas, the rhenium deposits in mainland China are mainly distributed in the following major regions:

- **Southwest:** Southwest China is the main production area of primary rhenium deposits in China. The so-called southwest here refers to Sichuan, Yunnan, Guizhou and Tibet. Sichuan Province is one of the most important rhenium production areas in the southwest. These rhenium deposits are mainly distributed in Ganzi and Aba in the province. The Happy Peak or Xilefeng rhenium deposit in Yunnan Province is one of the largest rhenium deposits in mainland China. In

addition, some other mines in the southwest also produce a small amount of rhenium, but the total output is relatively low.

- **Northeast China:** Northeast China is one of the regions with high rhenium production in mainland China, mainly distributed in Jilin, Liaoning, Heilongjiang and some neighboring provinces, such as some silver deposits in Inner Mongolia. Among them, Xinmin City, Liaoning Province is one of the main production areas of rhenium in Northeast China, and the rhenium ore produced is of good quality. However, the total rhenium production in Jilin and Heilongjiang provinces, which are also located in the Northeast, is relatively low.

- **Central China:** Some rhenium deposits have also been found in Henan, Shaanxi, Hubei, Hunan, and Yingtan, Jiangxi Province, which are rich in tungsten, molybdenum and copper ores. However, they are all small in scale³⁻⁵.

- **Other regions:** In addition to the aforementioned regions, a small number of rhenium deposits have also been found in other regions of mainland China, such as Jiangsu, Fujian, and some silver deposits in Gansu, but they are also small in scale³⁻⁶.

Overall, the known rhenium deposits in mainland China are widely distributed. However, these rhenium deposits are geographically remote and scattered, with poor infrastructure in the locations of the deposits, difficult mining, and high production costs. Affected by these factors, the overall rhenium ore production in mainland China is relatively low.

3.2 Deposit geology

The representative rhenium deposits and their geology discovered in mainland China are as follows:

- **Sichuan Muchuan-Mabian Re-Cu-Mo polymetallic deposit**

The sedimentary rocks of the Shaximiao Formation of the Middle Jurassic in the Sichuan Basin are traditionally important oil and gas production strata in southwest China, and are also a potential area for the development of various sedimentary deposits. The 1:50,000 regional geological surveys that began in the mid-twentieth century and the 1:10,000 comprehensive geochemical profiles survey projects in key work areas such as the rhenium-bearing rock series in recent years have unveiled the mystery of rhenium mineralization in the basin. Wu et al. conducted profile surveys, geological mapping, and dissections of typical deposits and showings in the Shaximiao Formation, supplemented by rock and mineral identification, multi-element chemical analysis, and lithology combination characteristics. He studied the sedimentary environment, material sources, and paleoclimate of the Shaximiao Formation, its typical deposits, showings, and rhenium-bearing rock series. In his master's thesis titled "Study on the Geological Conditions of Rhenium Mineralization in Mabian-Muchuan Area, Leshan City, Sichuan Province" completed in 2018¹¹, he concluded that under the action of epigenetic geology, rhenium migrates in the form of oxygen complexes dissolved in water. When a large amount of organic matter, feldspar and quartz particles and ore-forming materials are deposited in rivers and intermittent lakes at the same time, the organic matter in the water body adsorbs ore-forming materials copper, molybdenum and rhenium and deposits. During the mineralizing process, a large amount of H₂S gas released by the decomposition of organic matter dissolves in

water to produce a large amount of sulfur-containing solution, causing the deposition environment to change from an oxidizing state to a partially reducing state, so that sulfur-loving elements such as Mo, Cu and Re combine with S to form molybdenite and hydrous colloidal molybdenite ($\text{MoS}_2 \cdot n\text{H}_2\text{O}$), in which a considerable part of rhenium enters molybdenite, colloidal molybdenite and sulfide molybdenite in an isomorphous form.

In fact, as early as 1958, researchers noticed this type of mineralization and linked it with key words such as igneous action, hydrothermal activity, greisenization, ore-bearing quartz, and contact metamorphism¹². The origin of the mineralization is self-evident. More than 20 years later¹³⁻¹⁹, more researchers conducted more in-depth research on the geological characteristics and mineralization era of the mineralization. Among them, Shao concluded after studying the deposit that the occurrence state of rhenium in nature has not yet been fully clarified, and the geochemical characteristics of rhenium are also poorly understood¹³. At present, it is only known that basic igneous rocks contain more rhenium than acidic igneous rocks, and pegmatites contain more rhenium than their parent magma. Columbite, yttrium silicon beryllium ore, and tantalite in pegmatite veins all contain a certain concentration of rhenium, but it is most enriched in the hydrothermal stage after the magmatic period. It is generally believed that rhenium is mainly enriched in copper-molybdenum and copper deposits. This also seems to hint at the origin of the mineralization.

Shu believes that the mineralization geotectonic conditions, geological characteristics of the deposits, and ore-controlling factors of this rhenium mineralization belt are unique¹⁴. In the period of depression with deep regional dissection and distribution of algal reef ore source layers, the areas where northeast-trending tension-shear faults are developed or connected with them are all prospective areas for rhenium mineralization.

Some scholars have also found through research that this type of molybdenum-bearing sandstone is a new type of mineralization, namely sedimentary sandstone-type rhenium-molybdenum (osmium) mineralization¹⁶. The X-ray powder diffraction analysis shows that the fine-grained flaky molybdenum-bearing mineral is crystalline molybdenite. High-precision mass spectrometry analysis found that molybdenite contains dispersed Re, Os and platinum group elements, and the Os content is very high, which has important comprehensive utilization value. High-precision Re-Os isotope dating proves that the formation age of molybdenite is the same as that of host sandstone of the Mesozoic red bed basin. In addition, no signs of hydrothermal activity or tectonic influence were found at the time, so the preliminary conclusion that molybdenite is of syngenetic sedimentary origin was drawn.

Hao conducted scanning electron microscopy, energy spectrum and organic carbon isotope analysis on the bitumen closely related to rhenium and molybdenum enrichment and concluded that the mineralized sandstone in the mining area is the product of the delta front distributary channel sedimentary environment, rather than the relatively low-energy reduction distributary bay sedimentary environment, nor is it enriched by oxidation-reduction under surface conditions¹⁷. The bitumen in the deposit was formed by thermal cracking of the underlying Triassic Xujiahe Formation ancient oil reservoir. The extraordinary enrichment of rhenium and molybdenum has a close spatial and genetic relationship with the organic matter in the ancient oil reservoir.

Fan et al. conducted rhenium analysis on a large number of rocks and ores in this area and concluded that the mineralized layers in the central part of the Sichuan Basin are mainly rhenium

and molybdenum, the eastern part is mainly rhenium, molybdenum and copper, and the southern part is mainly copper, rhenium and silver²⁰. That is, there is a geochemical zoning phenomenon in the study area.

- **Huanglongpu Re-Mo carbonate vein-type deposit in east Qinling**

This deposit is a typical representative of the above-mentioned rhenium province in the central part of mainland China, and is also a relatively rare type of rhenium mineralization style. As the only carbonate vein-type Re-Mo deposit in the world²¹, the Huanglongpu Re-Mo ore field is located in the western section of the East Qinling metallogenic belt on the southern edge of the North China Platform, and is spatially controlled by the Lushi-Machaoying fault zone. Carbonate vein-type Re-Mo deposits are closely related to the Indosinian magmatic activity. The structure provides a favorable ore-bearing space, and the surrounding rock provides a small amount of ore-forming materials, forming the NW-trending Yuantou-Nianziping Re-Mo polymetallic mineralization belt and the NE-trending Xiping-Qinlinggou Cu-Mo mineralization belt. The Re and Mo contents are generally positively correlated. The ore-forming fluids are mainly magmatic hydrothermal fluids of the medium-high temperature silicate-carbonate-sulfate system. The ore-forming materials are mainly derived from mantle-derived igneous magma, which belongs to the late Indosinian orogeny and has roughly experienced three major mineralization periods.

Huang concluded that molybdenite is the main carrier mineral of rhenium²³. In different types of molybdenum deposits in the eastern Qinling region, the average content of Re in molybdenite is mostly between 10 and 20 ppm, but the molybdenite in the Huanglongpu carbonate vein-type molybdenum (lead) deposit has an average Re content of up to 152.5 ppm. Rhenium in molybdenite exists in the form of isomorphic substitution for molybdenum. The difference in rhenium content in molybdenite of these deposits mainly depends on the content of original rhenium in the ore-forming hot fluid. Molybdenite polytypes include 2H type and 2H+3R mixed type. Rhenium content and mineralization temperature have no effect on molybdenite polytype, so molybdenite polytype has no typical significance for molybdenum ore type.

The Comprehensive Research Team of the Shaanxi Geological Bureau conducted a study on the mineralization of the intermediate-acidic rock mass in the Shipu-Huanglongpu area of Luonan from 1979 to 1982, and concluded that there were at least two molybdenum mineralization periods in the Huanglongpu-Jinduicheng area. The eastern part of the study area is a favorable area for finding iron, molybdenum and copper, while the western part is a favorable area for finding molybdenum, rhenium and sulfur deposits.

The Ministry of Natural Resources' released report titled "'Resource Verification Report of Shanghe Molybdenum Deposit in Dashigou Deposit Section of Huanglongpu Molybdenum Ore Field in Luonan County, Shaanxi Province'" shows that the molybdenum ore resources have increased from the original 51,000 tons to 128,500 tons. The newly discovered associated ore has a rhenium metal content of 176.11 tons, making it the largest rhenium ore producing area in China²⁴. The Re content of the Dashigou molybdenum deposit ranks first among the molybdenum deposits in the eastern Qinling Mountains in Shaanxi, and is also among the top in similar deposits in the country²⁵⁻²⁶.

- **Jigongcun Re-Mo deposit in Tibet**

The Jigongcun Re-Mo deposit in Qushui County, Tibet, is a quartz vein-type rhenium deposit with a prominent rhenium-rich feature²⁷. The rock mass in the area is mainly granodiorite and

quartz diorite with an age of 51.8 ± 0.5 Ma, and the mineralization age of the deposit is 21.8 ± 6.2 Ma. The hydrothermal alteration distributed in the fault zone and the rock mass on both sides is potashization, epidote-chloriteization and pyrite-sericite quartzization from deep to shallow. The mineralization can be divided into quartz-potassium feldspar-anhydrite stage, quartz-pyrite stage, quartz-molybdenite stage, quartz-galena stage, and molybdenum epigenetic oxidation stage from early to late. Among them, rhenium and molybdenum are mainly developed in the quartz-molybdenite stage. The rhenium-containing metal minerals are mainly molybdenite, followed by U-Ti oxides and bismuth tellurides. The Re content in molybdenite is mostly between 0.10% and 0.30%, with a maximum of 0.88% and an average of about 0.20%. The Re content in molybdenite is $(1334-2148) \times 10^{-6}$, with an average of 1606×10^{-6} . The Re content in U-Ti oxide is 0.02% on average, with a maximum of 0.07%. The Re content in bismuth-telluride is 0.13%-0.19%, with an average of about 0.15%. The ore-forming fluid in the mining area belongs to the $\text{CO}_2\text{-H}_2\text{O-NaCl}$ system, mainly H_2O solution inclusions (L1 and L2) and $\text{CO}_2\text{-H}_2\text{O}$ inclusions (C1 and C2). Among them, L1, C1 and C2 fluid inclusions are the main ones, followed by a small amount of L2 and single-phase fluid inclusions. The homogenization temperature range of each stage of the ore body I is: $251.4\sim 311.4$ °C in the quartz-pyrite stage, $232.2\sim 295.7$ °C in the quartz-molybdenite stage, and $180.7\sim 239.4$ °C in the quartz-galena stage. The quartz-potassium feldspar-anhydrite stage in the ore body III is $263.0\sim 325.6$ °C, quartz-pyrite stage is $246.5\sim 303.5$ °C, quartz-molybdenite stage is $201.0\sim 270.0$ °C, and quartz-galena stage is $180.0\sim 218.5$ °C. From the early stage of mineralization to the late stage of mineralization, the ore-forming fluid showed an evolution trend from medium temperature and medium salinity to low temperature and low salinity.

The Jigongcun molybdenum deposit in Tibet is a typical rhenium-rich molybdenum deposit⁵, with an estimated molybdenum ore content of 48.8 million tons, molybdenum metal content of 63,400 tons, and an average molybdenum grade of 0.13%. The rhenium metal content is 166.33 tons, with an average grade of 3.47×10^{-6} . The ore body is mainly vein-like and occurs in the ductile shear zone in the granodiorite, with a time difference of about 30 Ma between diagenesis and mineralization. Hydrothermal alteration mainly includes silicification, sericitization, kaolinization, etc., but is limited to the granodiorite in and on both sides of the fault. Molybdenite is mainly vein-like and thin-film-like in quartz vein fissures or in the altered granodiorite at the edge of the fault in the form of dissemination. The mineral assemblage is mainly pyrite-quartz, molybdenite \pm pyrite \pm galena-quartz, with very small amounts of chalcopyrite, Bi-Te sulfide, U-Ti oxide, etc. Rhenium is mainly found in molybdenite, and trace amounts of rhenium are also found in sulfides such as chalcopyrite.

- **The Zagestan sandstone-type Re-U deposit in Xinjiang**

The Zajistan sandstone-type U-Re-Se-Mo polymetallic deposit in the Yili Basin of Xinjiang was called the 511 uranium deposit during the "secret era" in mainland China^{5-6,28}. The uranium ore bodies are produced in the interlayer oxidation-reduction transition zone in the Jurassic Shuixigou Group lithic quartz sandstone and feldspar lithic sandstone, and are of epigenetic alluvial origin. Rhenium minerals, which exist in the form of rhenium sulfides or metal organic compounds combined with humus, are enriched in the front line of the interlayer oxidation zone and its inner and outer sides in a vesicular shape, which is roughly consistent with the distribution range of the uranium ore bodies, but biased towards the reduction zone. Selenium is enriched in the inner side of the front line of the interlayer oxidation zone in a lens shape, biased



towards the oxidation zone. The uranium ore contains abundant strawberry-shaped, star-shaped colloidal pyrite, organic matter and charcoal, as well as a small amount of pyrrhotite, marcasite and limonite. Uranium appears in the form of microscopic particles of uranium-containing minerals such as pitchblende and uraninite, or is present in sandstone in an adsorbed form. Rhenium may migrate with water between oxygen-containing layers in the form of $Re7^+$ ion complexes, and be enriched in the interlayer oxidation-reduction transition zone under the reduction of organic matter and sulfur. U is highly positively correlated with associated elements such as Re, Mo, and Se. The average content of Re in uranium ore is 0.71×10^{-6} , Mo 54.16×10^{-6} , and Se 1.40×10^{-6} .

4. Characteristics of rhenium ore in Mainland China

In recent years, mainland China has achieved remarkable results in the exploration of rhenium deposits. New associated rhenium deposits have been discovered in Guizhou, Hubei, Henan and other provinces, as well as independent rhenium mineralization zones suspected to be dominated by rhenium, namely sedimentary sandstone rhenium deposits in Muchuan, Sichuan (Table 3-5). As of the end of 2021, China has obtained a total of 787.41 tons of rhenium ore resources²⁸.

Table 4. A brief statistical table of rhenium deposits discovered in mainland China (modified from Huang et. al.²⁸)

Series #	Province/region	City	County	Deposit name	Cumulative resource (t)	Average grade (%)
1	Inner Mongolia	Chifeng	Al Horqin Banner	Laojiagou Mo	6	0.004 125
2	Liaoning	Huludao	Lianshan District	Lingqian Mo	1.29	0.005 100
3	Liaoning	Huludao		Xintaimen Mo	7	
4	Heilongjiang	Heihe	Nenjiang County	Duobaoshan Cu-Mo	75	
5	Heilongjiang			Tongshan Cu	24	
6	Jiangsu	Zhenjiang	Jurong City	Tongshan Mo-Cu	2	1.000 000
7	Fujian	Nanping	Wuyishan City	Pingdi	5.29	
8	Henan	Luoyang	Luanchuan	Luotuoshan pyrite	1.5	0.003 600
9	Henan			Sandaozhuang Mo-W	33.38	300~0.002
10	Henan			Lengshui-Chitudian Mo-Pb-Zn	146	0.001 000
11	Henan	Xinyang	Guangshan	Qianechong Mo	15.14	0.140 000
12	Hubei	Huangshi	Daye City	Houtoushan Mo-Cu	1	0.034 000
13	Hunan	Chenzhou	Guiyang	Baoshan	6	
14	Hunan	Changsha	Liuyang City	Longwangpai	78.3	0.000 600
15	Tibet	Lhasa	Qushui	Jigongcun Mo	164.31	
16	Shaanxi	Weinan	Hua	Jinduicheng Mo	41.85	0.000 327
17		Shangluo	Luonan	Xigou Mo	7.24	
18				Huanglongpu Mo	53.82	

**Table 5.** A brief geology & geochemistry of the rhenium deposits in mainland China (modified from Huang et al.²⁸)

Origin	Deposit	Commodity	Type	Metallogenic epoch			Dominant commodity			Re		Mining situation	
				Orogeny	Age (Ma)	Dating method	Commodity	Resource (10,000 t)	Size	Resource (t)	Size		
Jinxián, Anhui	Chenling Mo	Mo, Cu, Re	Porphyry	Yanshan			Mo	6.21	Medium	29.42	Medium	No	
Yanqing, Beijing	Dakezhuang Mo	Mo, Re	Continental volcanic		137.6±3.7		Molybdenite	Mo	1.04		0.38	Small	No
Wuyishan, Fujian	Pingli Mo	Mo, Pb, Re	Magmatic hydrothermal		107.4±3.3		Re-Os	Mo	2461		5.29	Medium	Yes
Gutian, Fujian	Xichao Mo	Mo, Re	Porphyry		113.4±0.9		Molybdenite	Mo	0.25	Small	1.52	Small	Stopped
							Re-Os						
Énping-Yangchun, Hubei	Chunwan Mo	Mo, Re	Porphyry					Mo	21.24		40.25	Medium	No
Yangchun, Hubei	Shilu Cu-Mo	Cu, Mo, Ag, Re	Skarn		104.34±0.66		Molybdenite	Cu, Mo	28.97		2.887	Small	Stopped
		Mo, Hg, Tl, V	Epithermal										
Kaiyang, Guizhou	Baimadong Hg	Re, Ga, B, Sb	Hydrothermal					Hg	2.4232		20	Medium	Unknown
	Luotuoshan pyrite	S, Cu, Zn, W, Re	Skarn		137.1 ~ 138.4		Molybdenite Rb-Sr	S	756.9 Ore	Large	1.5	Small	Yes
	Nannihu Mo-W	Mo, W, Re	Porphyry-skarn		143.4 ~ 146.5		Molybdenite Re-Os	Mo, W	67.6910 ; 0.6061	Large	30.79		Yes
	Sandaozhuang W	Mo, W	Skarn		143.4 ~ 146.5		Molybdenite Re-Os	Mo, W	77.36 ; 51.12		22		Yes
	Shangfanggou Mo	Mo, Re	Porphyry-skarn		144.8±2.1		Molybdenite Re-Os	Mo	72.23	Large	81.258	Large	Yes
Guangshan, Henan	Qianchong Mo	Mo, Ag, Re		128.7±7.3		Molybdenite Re-Os	Mo	50.738 8		15.14	Medium	Yes	
	Duobaoshan Cu-Mo	Cu, Mo, Re Cu, Mo, Se, Re	Porphyry	475.1±5.1		Molybdenite Re-Os	Cu	315.05		75	Large	Yes	
Nenjiang, Heilongjiang	Tongshan Cu	Cu, Mo, Au, Cd, Re		461±1		LA-ICP-MS Zircon U-Pb	Cu	32.983	Medium	24	Medium	Yes	
Xunke, Heilongjiang	Cuihongshan polymetallic	Fe, Re, Mo, W, Zn, Cu, Pb, Sn, Cd, In, Se, Te	Skarn	201.6±1.4		Molybdenite Re-Os	Fe	6 865.82	Large	0.6	Small	Stopped	
Daye, Hubei	Houtoushan Mo-Cu	Mo, Cu, Re	Magmatic hydrothermal				Mo, Cu	0.012 9 ; 0.094 0	Small	1.08		Yes	
	Tongkoushan Cu	Cu, Mo, Ag, Se, Te, Re		143 ~ 129		Mica Ar-Ar	Cu	30.77	Medium	5.9	Medium	Yes	
Yangxin, Hubei	Lijawan Cu polymetallic	Cu, Au, Ag, Mo, S, Se, In, Cd	Porphyry-skarn	138 ~ 137		SHRIMP Zircon U-Pb	Cu	7.75	Small	0	Showing	Yes	
Liuyang, Hunan	Longwangpai Mo-W	W, Mo, Re	Magmatic hydrothermal	146.3±1.8		Molybdenite Re-Os	W + Mo	2.67		78.3	Large	No	
Yongji, Jilin	Daheishan Mo	Mo, Cu, S, Ga, Re	Porphyry	168.2±3.2		Molybdenite Re-Os	Mo	21.55	Large	3	Small	Yes	
	Guokuidingzi Cu	Cu, Ag, Re, Ga, Ge	Magmatic hydrothermal	250±1.5		Molybdenite Re-Os	Cu	0.51		0.4	Showing	Stopped	
Jurong, Jiangsu	Tongshan Cu-Mo	Cu, Mo, Au, Ag, Re	Skarn	170		Garnet U-Pb	Cu, Mo	1.196 5 ; 0.514 4	Small	4	Small	Yes	
	Xintaimen Mo	Mo, Pb, Zn	Porphyry	183±3		Molybdenite Re-Os	Mo, Zn	0.069 9 ; 0.016 3		7	Medium	Yes	
Huludao, Liaoning	Yangjiazhangzi Mo	Mo, Pb, Zn	Skarn	187 ~ 191		Molybdenite Re-Os	Mo	2.45	Medium	1.39	Small	Yes	
Alukeerqin, Inner Mongolia	Laojiagou Mo	Mo, Re	Porphyry	234.9±3.1		Molybdenite Re-Os	Mo	8.321 9		5.728	Medium	No	
Xinbaerhuoyuqi, Inner Mongolia	Wunugetushan Cu-Mo	Mo, Cu, Re, Ag, Au		177.4±2.4		Molybdenite Re-Os	Mo, Cu	34.67 ; 130.24		99.1		Yes	
	Huanglongpu Mo	Pb, Mo, Fe Re, Te, Se	Skarn	221		Molybdenite Re-Os	Mo	12.2	Large	53.82	Large	Yes	
Luonan, Shaanxi	Mulonggou Fe	Fe, Mo, Cu, Zn, S		151±1		LA-ICP-MS Zircon U-Pb	Fe	1841.96		3.18	Small	Stopped	
	Xigou Mo	Mo, Re	Magmatic hydrothermal	225.1±1.4		Molybdenite Re-Os	Mo	1.76	Medium	6.46	Medium	Yes	
Huaxian, Shaanxi	Jinduicheng Mo	Mo, Cu, S, Se, Re		129 ~ 140		Molybdenite Re-Os	Mo	96.97	Large	118.7	Large	Yes	
Sangrixian, Tibet	Mingze Cu polymetallic	Cu, Mo, Re	Porphyry	Himalayan	30.26±0.69	Molybdenite Re-Os	Cu, Mo	13.09 ; 6.23		16.64		No	
Hami, Xinjiang	Jingerquan-Baishan Mo	Mo, Re, Ag		Indosinian	224.8±4.5	Molybdenite Re-Os	Mo	3.55	Medium	29.15	Medium	No	
Chabuexibo, Xinjiang	Langka U-Re	U, Re	Epithermal	Yanshan	J ₂		U	0.459 96		21.7		Unknown	

Most of the known rhenium deposits in mainland China are paragenetic and/or associated minerals of molybdenum and/or copper-molybdenum deposits. Relevant researchers have estimated that China's rhenium resources are about 4,000 tons by analyzing the Re-Os isotope data of molybdenite in 147 such deposits²⁸⁻³¹. Among the more than 70 porphyry copper deposits counted, 10 of them have associated rhenium resources exceeding 50 tons (Table 3-5). There are 18 associated and/or paragenetic rhenium deposits in China, with a total rhenium resource of 669.12 tons, an increase of 39.5%.

From the perspective of rhenium mineralization age, most of the known rhenium deposits in mainland China were formed in the Jurassic, that is, during the Yanshan orogeny. The next ones were the Indosinian, Caledonian and Himalayan periods. This shows the important influence of Mesozoic plate tectonic movement on rhenium mineralization (Tables 3 and 5).

Some mainland Chinese scholars believe that China's rhenium ore production capacity has been significantly improved in recent years and has become the world's second largest producer of rhenium products²⁸. However, the grade of China's rhenium ore is low, and its comprehensive utilization technology lags behind that of the international community. The secondary recycling and utilization of rhenium resources is still immature, and there is a problem of insufficient resource recycling and development and utilization scale. In addition, the rhenium industry in mainland China is still in its infancy, with breakthroughs to be made in the deep processing of rhenium mineral products and high-tech materials. Currently, it mainly relies on imports. However, China is strengthening cooperation with countries rich in rhenium mineral resources through the "Belt and Road" initiative to enhance its ability to obtain overseas rhenium mineral products.

Relevant scholars further pointed out that with technological advancement and increasing market demand, the demand for rhenium will continue to grow²⁸⁻³¹. It is expected that in the next 10-20 years, the application of rhenium in China will become more diversified, and the demand for rhenium will therefore reach its peak. However, the country's existing domestic rhenium resource reserves are difficult to meet demand. To this end, it is recommended that the Chinese government actively evaluate the potential of rhenium ore resources, improve comprehensive utilization technology, and strengthen the secondary recycling of rhenium. At the same time, a strategic reserve mechanism for rhenium will be established to ensure resource security and further improve the security of rhenium resources.

5. Types of primary rhenium deposits in mainland China

Based on the above information, the primary rhenium deposits currently known in mainland China can be divided into the following types (Table 6), which are briefly discussed below.

Table 6. Types of known primary rhenium deposits in mainland China

Industrial type	Genetic type	Metallogenic time		Potential commodity association
		Orogeny	Age (Ma)	
Associated/symbiotic	Porphyry	Caledonian, Indosinian , Yanshan, and/or Himalayan	30.3 - 475.0	Mo, Cu, Pb, Zn, Ag, Au, S, Cd, Re, Se, In, Ga, Te
	Skarn	Indosinian and Yanshan	137.1 - 221.0	W, Mo, Fe, S, Sn, Cd, In, Se, Te, Cu, Pb, Zn, Au, Ag, Re
	Continental volcanic	Yanshan	137.6 ± 3.7	Mo, Re
	Magmatic hydrothermal	Indosinian and/or Yanshan	107.4 - 250.0	Mo, Cu, Pb, W, Re, Ag, Ga, Ge
	Hydrothermal	Yanshan		Re, Ga, B, Sb, Hg
	Epithermal	Yanshan	104.34 ± 0.66	Cu, Mo, Ag, Re, Mo, Hg, Tl, V, U
	Carbonate vein	Yanshan, Indosinian	222	Mo, Pb, Re
	Quartz vein	Himalayan	22.5	Mo, Re
Independent (multimetal)	Sandstone	Yanshan	202.0 - 206.0	Re, Cu, Mo, Os, U

Compared with the similar minerals in other countries around the world, the primary rhenium deposits in mainland China have both the same or similar features, but also their own unique features.

As for the first category of associated and/or symbiotic rhenium deposits, mainland China and the world have the following genetic types: porphyry type, skarn type and the composite type of the two; magmatic hydrothermal type, other genetic hydrothermal type, and/or mixed type of different hydrothermal fluids; sandstone-type rhenium Re-Cu deposits including the (reduced-facies) sandstone strata-bound deposits, such as the Zhezkazgan sandstone copper deposit in Kazakhstan, and the Mansfield-type multi-element copper deposits in the Permian copper-bearing sandstone-shale in Eastern Europe, which contain extremely high rhenium, and rhenium has even been extracted from them; sandstone-type Re-U deposits, such as the uranium (scandium) sandstone deposits in the Colorado Plateau of the United States; sedimentary transformation-type associated rhenium deposits: under certain geological conditions, rhenium and/or its compounds are enriched and formed in certain sedimentary rocks through hydrothermal activities generated by deep buried rock bodies; volcanic rock-type rhenium deposits; and rhenium mineralization in black shales, such as the high content of rhenium and platinum group found in the Devonian black shales in the Yukon region of Canada³², and similar rhenium mineralization has also been found in Hunan and Guizhou, China. In a sense, this rhenium-bearing black shale-type rhenium mineralization may be an independent rhenium deposit similar to the sandstone-type rhenium mineralization in mainland China.

Similarly, in terms of the first category of associated and/or symbiotic rhenium mineralization, mainland China has discovered genetic types that have not yet been discovered in other countries, such as carbonate vein type, quartz vein type and epithermal rhenium mineralization. Of course, this difference may be largely a matter of time, that is, the international community



may find it soon. In addition, differences in the understanding or judgment criteria of the genetic type of rhenium mineralization will also cause this temporary result.

The greater difference between the known rhenium mineralization in mainland China and the international community lies in the so-called independent rhenium mineralization in mainland China. This is actually the discovery of rhenium polymetallic mineralization in China, which has not been discovered or reported overseas so far. Of course, this so-called independent rhenium mineralization in mainland China still needs more exploration work to verify. The fact is that this so-called independent rhenium mineralization is polymetallic mineralization, not independent rhenium mineralization in the pure sense.

However, some sources believe that the skarn-type Merlin molybdenum-rhenium deposit in Queensland, Australia is one of the few independent rhenium deposits, with a rhenium grade of up to 22.7 g/t. However, compared with other types of deposits, the total reserves of this rhenium deposit are relatively small³³.

In terms of the mineralization era, the known rhenium mineralization in mainland China is also different from that in the international community. In general, the mineralization era of the global rhenium-rich deposits spans a wider range, from the Paleoproterozoic to the Cenozoic, but mainly in the Cenozoic and Mesozoic, among which the Himalayan and Yanshanian are the most developed, followed by the Caledonian and Indosinian. In terms of origin, global rhenium mineralization is mainly distributed in the Circum-Pacific metallogenic belt and the Tethys metallogenic belt. Among them, the most representative rhenium deposits formed in the Himalayan period are the most, such as the Cerro Verde (62 Ma) in Peru, Bingham (37 Ma) in the United States, Maronia (29 Ma) in Greece, Sar Cheshmeh (12.5 Ma) in Iran, and the El Teniente (5.4 Ma) porphyry copper-molybdenum deposit in Chile. Representative deposits of the Caledonian period include the Aksug porphyry copper-molybdenum mine (403 Ma) in Russia. There is also a very small number of rhenium deposits formed in the Paleoproterozoic, such as the Merlin molybdenum-rhenium deposit (1,528 Ma) in Australia.

The known rhenium mineralization in mainland China mainly occurred in the Yanshanian period, with representative deposits such as the porphyry copper-molybdenum polymetallic deposit in Xiongcu, Tibet (166 Ma), the porphyry copper deposit in Dexing, Jiangxi (171 Ma), the Jinduicheng in Shaanxi (138 Ma) and the Daheishan porphyry molybdenum deposit in Jilin (169 Ma). The second is the Indosinian period, with representative deposits such as the porphyry molybdenum deposit in the East Gobi of Xinjiang (211.7 Ma) and the carbonate vein-type molybdenum-lead deposit in Huanglongpu, Shaanxi (222 Ma). The third is the Himalayan period, such as the quartz vein-type molybdenum deposit in Jigongcu, Tibet (22.5 Ma); and the Caledonian period, such as the Bainaimiao porphyry copper-molybdenum polymetallic deposit in Inner Mongolia (433.9 Ma) and the Duobaoshan porphyry copper-molybdenum deposit in Heilongjiang (474.5 Ma).

6. Discussion

The unique geographical location and rich geological structure of mainland China determine that the rhenium resources produced here have both similarities with similar resources in other



continents around the world and their own uniqueness. This is consistent with the fact that the distribution of chemical elements on the entire earth, especially on the earth's surface, is uneven.

Similar to most rare elements in the world, rhenium in mainland China mainly appears in the form of associated and/or paragenetic minerals. The world's rhenium resources are mainly contained in porphyry copper and/or copper-molybdenum deposits, and the resource volume accounts for about 80%. Typical examples are the Ajo porphyry copper-molybdenum deposit in Arizona, USA and the Chuquicamada porphyry copper-molybdenum deposit in Chile. The same is true for mainland China: porphyry associated and/or paragenetic rhenium deposits are the main type, but not limited to copper or copper-molybdenum deposits. Rhenium mineralization in mainland China is associated and/or paragenetic with porphyry copper, copper-nickel, and copper-molybdenum deposits, and is also paragenetic and/or associated with porphyry lead and zinc deposits.

In this regard, more associated or symbiotic deposits will be discovered in the Yangtze River Basin, the Qinghai-Tibet Plateau, the Northwest and the three provinces of Northeast China in the near future,, which are rich in porphyry copper, copper-molybdenum and copper-nickel deposits. Some researchers have already noticed this³⁴.

An interesting phenomenon is that there is a significant difference in the average rhenium content in molybdenites formed by different orogenic movements: the rhenium content in molybdenites formed in the Himalayan and Yanshan periods is higher, followed by the Indosinian and Caledonian periods. In general, the newer the formation of molybdenite, the higher the rhenium content and the greater the resource reserves³⁵. Golden et al. calculated the average rhenium content of molybdenite in molybdenum deposits formed in three geological periods around the world, which was 115×10^{-6} during 2,910~1,870 Ma, 335×10^{-6} .

Compared with traditional bulk minerals such as copper, lead, zinc and iron deposits, the exploration and research of rhenium deposits started much later. It is believed that more brand new and known types of rhenium deposits will be discovered over time. For example, trace amounts of rhenium have been found in ultramafic rocks in Ukraine in recent years, rhenium mineralization has been found in volcanic rocks in Hokkaido, Japan, in the fumaroles of Kudriave Volcano in Russia, and in mineralization related to platinum group elements in ultramafic rocks³⁶.

In the Ni-Mo-PGE sulfide-rich layers of the Lower Cambrian in southern China, the grade of rhenium in some areas has reached or even exceeded its industrial grade, with the highest rhenium in a single sample reaching 33×10^{-9} . There is every reason to believe that more new types of rhenium deposits will be discovered in the future³⁶.

7. Conclusions

The uneven distribution of various chemical elements on the earth itself, as well as the unique and colorful geological background of mainland China, determines that the primary rhenium deposits produced here have similarities with similar resources in other continents around the world, but also have their own uniqueness.



In particular, mainland China has the Qinghai-Tibet Plateau, which is still geologically very active, resulting in the frequent discovery of some minerals independent of the world in the western part of mainland China, such as the independent tellurium deposit discovered in 1993 and the newly discovered independent rhenium deposit in western Sichuan Province, part of the Plateau. This is the key difference between mainland China and other parts of the world. I believe that in the near future, more special mineralization types and minerals that will attract the attention of the international geological community will be discovered in the Qinghai-Tibet Plateau, including the rhenium deposit discussed in this article.

In addition to the Qinghai-Tibet Plateau, more and more associated and/or symbiotic rhenium deposits will be found in the Yangtze River Basin, Qinling Mountains, Northwest China and Northeast China, which are rich in porphyry copper, copper-molybdenum and copper-nickel deposits.

China's exploration, development, production and research on rare element rhenium deposits are still in the initial stage, and there is a lot of room for development in all aspects. At the same time, there is also room for improvement in the beneficiation, smelting and orderly development and control of the downstream market of rhenium ore products in the mainland.

8. References

1. China Economic Industry Research Institute. 2023. Analysis of China's rhenium production, demand and market. <https://www.163.com/dy/article/15JJS59A05563K26.html>. Retrieved December 20, 2024 (in Chinese).
2. The Fifth Geological Brigade of Hebei Bureau of Geology and Mineral Resources. 2023. Geological Vision | Top Aspirations, Waiting for You "Rhenium". https://mp.weixin.qq.com/s?__biz=MzIxOTI4MTU4NA==&mid=2650515426&idx=2&sn=67d1b4cc97697df394bbbf70268a9d2c&chksm=8fd2a63db8a52f2bfc36766fb4d229b1ceb3a8b8ce0e94e2cdb928c7041368830d85e075ca16&scene=27. Retrieved December 20, 2024 (in Chinese).
3. *Earth Science* Editorial Department. July 22, 2022. So "rhenium" is like this. https://mp.weixin.qq.com/s?__biz=MzIzNTAzODYxNQ==&mid=2649683519&idx=1&sn=acb7f21bd77bae40b1865e2875103677&chksm=f0f764c7c780edd1ceb8dfdbc3b74c39caac63f6601b78764fd98027f1fabd4aa00315e37bbd&scene=27. Retrieved December 20, 2024 (in Chinese).
4. Zhiyan boutique report. 2020-12-19 06:26. Global rhenium ore production and distribution in 2019: China's production accounts for only 5.1%, which is not dominant at all. <https://www.chyxx.com/industry/202012/917635.html>. Retrieved December 20, 2024 (in Chinese).
5. Zhou CJ; Zhang GY & Zhang DC. Types, element occurrence forms and enrichment mechanisms of rhenium metal deposits. *Bulletin of Geological Science and Technology*, 2021, 40 (4): 115-130. DOI: 10.19509/j.cnki.dzqk.2021.0431 (in Chinese with English abstract).
6. Huang, F; Wand, DH; Wang Y; Jiang, B; Li, C & Zhao, M. 2019. Study on metallogenic regularity of rhenium deposits in China and their prospecting direction. *Acta Geologica Sinica*, 93 (6): 1252-1269. DOI: CNKI: SUN:DZXE.0. 2019-06-007 (in Chinese with English abstract).
7. Tan, Q. 2006. Russia recently discovered the world's first pure rhenium ore. *Functional Materials Information*, 3 (5): 1 (in Chinese with English abstract).
8. U.S. Geological Survey. January 2024. Rhenium. Mineral Commodity Summaries, 146-147. <https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-rhenium.pdf>. Retrieved December 20, 2024.
9. Xu, D; Chen, PQ, Cheng, JG, Cao, QG, Chen, KK & Zhao, PC. Current status and development trend of rhenium recovery technology from alloy waste. *Metal Functional Materials*, 2020, 27 (04): 1-9.
10. Fang, J; Wu, DD; Wen, SM; Zhang, S & Lin QQ. Research progress on comprehensive recovery and utilization of scattered metal rhenium resources. *Mineral Conservation and Utilization*, 2020 (005): 040 (in Chinese with English abstract).



11. Wu, JW. Study on geological conditions of rhenium mineralization in Mabian-Muchuan area, Leshan City, Sichuan Province. *Master's degree thesis*, Chengdu University of Technology, 2018 (in Chinese with English abstract).
12. Wang, EY. Geological characteristics and mineralization age of Muchuan Taiping sandstone-type rhenium-molybdenum (osmium) deposits. *Geology and Exploration*, 1958 (8): 16-21 (in Chinese with English abstract).
13. Shao, JL. Geological characteristics and mineralization age of Muchuan Taiping sandstone-type rhenium-molybdenum (osmium) deposits. *Geology and Exploration*, 1984 (12) (in Chinese with English abstract).
14. Shu, JW. 1985. Geological characteristics and mineralization age of the Taiping sandstone-type rhenium-molybdenum-osmium deposit in Muchuan. *Geotectonics and Mineralization*, 1985 (3): 84-90 (in Chinese with English abstract).
15. Huang, DH. Geological characteristics and mineralization age of the Taiping sandstone-type rhenium-molybdenum-osmium deposit in Muchuan. *Journal of Petrology and Mineralogy*, 1992 (1): 74-83 (in Chinese with English abstract).
16. Cao, ZM & Luo, YN. 2002. Geological characteristics and mineralization age of the Taiping sandstone-type rhenium-molybdenum-osmium deposit in Muchuan. *Acta Geologica Sinica*, 76 (1): 95-99. DOI:10.3321/j.issn:0001-5717.2002.01.012 (in Chinese with English abstract).
17. Hao, XF; Tang, Y; Peng, Yu; Pan, M; Yang, R & He, Y. 2023. Geological characteristics and super-enriched mineralization of sandstone-type rhenium-molybdenum deposits in Leshan area, southwestern Sichuan Basin. *Geology and Exploration*, 59 (4): 734-746. DOI:10.12134/j.dzykt.2023.04.004 (in Chinese with English abstract).
18. You, XJ. 2024-12-21. Evaluation report on rhenium polymetallic ore resources in Muchuan-Mabian area, Sichuan Province (in Chinese with English abstract).
19. Zhang, JY. 2024. Characteristics of polymetallic rhenium-bearing sand bodies in Muchuan-Mabian. *Sichuan Geological Journal*. DOI: CNKI:SUN:SCDB.0.2014-03-015 (in Chinese with English abstract).
20. Fan, JB; Yang, R; Liang, B; Peng, Y; Pan M & Tang Y. Application of portable XRF in rapid identification of rhenium-bearing ore bodies in Sichuan Basin. *Mineral Exploration*, 2024, 15 (1): 117-126 (in Chinese with English abstract).
21. Duan, XY; Li WC; Wang, HY; Huang, F; Gao, HF; Yang, T; Yang, S; Song, GS & Yao FS. 2024. Mineralization characteristics and prospecting prediction of carbonatite vein-type rhenium-molybdenum deposits in Huanglongpu ore field, East Qinling. *Northwest Geology*, (5). DOI: 10.12401/j.nwg.2024045 (in Chinese with English abstract).
22. Huang, DH. 1992. Rhenium content and polymorphic characteristics of molybdenite in molybdenum deposits in the eastern Qinling region. *Journal of Rocks and Mineralogy*, (1) (in Chinese with English abstract).
23. Xue, ZL. 1982. Research report on the mineralization of small intermediate-acidic rock bodies in Shipo-Huanglongpu area, Luonan County, Shaanxi Province. *Comprehensive Research Team of Shaanxi Provincial Geological Bureau*. File No.: 67224.
24. Anonymous. Reserves of a molybdenum mine in Shaanxi Province increased dramatically, and the rare metal rhenium is very eye-catching. *China Molybdenum Industry*, 2011, 35 (2):32-32.
25. Chen, FG. 1987. Rhenium in molybdenite in the molybdenum deposits (mainly Dashigou deposit) in the eastern Qinling Mountains, Shaanxi Province. *Shaanxi Geology*, (2): 61-69. DOI: CNKI:SUN:SXDY.0. 1987-02-007.
26. Zhao, H; Zhang, QD; Yu, XM; Yang, DD; Li, ZJ; Huang, Q & Zhang CH. 1984. Preliminary discussion on geological characteristics and genesis of Dashigou molybdenum (rhenium) deposit. *Northwest Geology*, (03): 27-34. DOI: CNKI:SUN:XBDI.0. 1984-03-004 (in Chinese with English abstract).
27. Zhou, CJ. 2021. Study on geological and ore-forming fluid characteristics of Jigongcun rhenium-molybdenum deposit in Tibet. *Master's degree thesis*, Chengdu University of Technology.
28. Huang, F; Zhao, YB; Wang, Y; Chen, ZZ & Li DX. 2024. Resource characteristics and current situation of exploration, development and utilization of rhenium in China. *China Mining Magazine*, 33(4): 23-31. DOI: 10.12075/j.issn.1004-4051.20240376.
29. Li DX & Wang, DH. 2024. *China Mineral Geology: Rare Metal Minerals Volume*. Beijing: Geological Publishing House (to be published).
30. China Mineral Geology Project Office. 2016. *Technical Requirements for the Compilation of Provincial Mineral Geology of China Mineral Geology*.
31. Wu, X; Li, LP; Zhang, WZ & Zhang, X. 2008. Properties of rhenium and its resources distribution. *Express Information of Mining Industry*: (11): 67-69.
32. Horan, MF; Morgan JW; Grauch, RI; Coveney Jr., RM; Murowchick, JB & Hulbert LJ. 1994. Rhenium and osmium isotopes in black shales and Ni-Mo-PGE-rich sulfide layers, Yukon Territory, Canada, and Hunan and



Guizhou provinces, China. *Geochimica et Cosmochimica Acta*, 58 (1): 257-265. DOI: [https://doi.org/10.1016/0016-7037\(94\)90463-4](https://doi.org/10.1016/0016-7037(94)90463-4).

33. Wu, Y; Ju, N; Ma, W; Guo, CL; Wu, TT & Zhou YH. December 26, 2024. Distribution, main types and current status of exploration and development of rhenium deposits. <https://mp.weixin.qq.com/s/IXprHjbtY6vc25ptz1uKKQ>. Retrieved December 28, 2024 (in Chinese).

34. Zhou, TF; Fan, Y; Chen, J; Xiao, X & Zhang, S. 2020. Critical metal resources in the middle-lower Yangtze River Valley Metallogenic Belt. *Chinese Science Bulletin*, 65(33): 3665-3677. DOI: 10.1360/TB-2020-0347.

35. Chen, XF; Chen XF; Li, N; Ye, JH; Chen, YM; Zhao, HJ & Zhang, WB. 2019. Distribution characteristics and development & utilization status of global rhenium resources and its enlightenments. *China Mining Magazine*, 28 (5): 7-12, 23. DOI: CNKI: SUN:ZGKA.0.2019-05-002.

36. Morgan, J; Stein, H; Hannah, J & Markey R. 2000. Re-Os study of Fe-Ti-V oxide and Fe-Cu-Ni sulfide deposits, Suwalki Anorthosite Massif, northeast Poland. *Mineral Deposita*, 35: 391-401. <https://doi.org/10.1007/s001260050251>.

Data availability

The data that support the findings of this study is available from the author upon reasonable request.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI tools declaration

The author declares that he has not used Artificial Intelligence (AI) tools in the creation of this article.





Original Article

The past, present and future of printing technology

—Preface to the monograph titled *Standards and Energy Saving in Printing Ink Curing and Drying Processes*

Guorui Zhang¹ 

Abstract

Advances in science and technology, people's pursuit of aesthetics, and evolution of anti-counterfeiting techniques have driven changes in printing substrates, inks, and printing processes. With increasing printing speeds, the requirements for ink curing and drying have become more stringent. The factors affecting ink curing and drying are complex and energy-intensive. This book primarily discusses how to develop printing process standards to address these challenges.

Key words: standardized processes; multifactorial; drying standards; energy-saving


Affiliation Info: ¹Independent Researcher, 15935 106A Avenue, Surrey, BC, Canada V4N, 3J2

Authors' Contact Info: Zhang, GR: guoruizhang1960@gmail.co

Citation: GR Zhang. 2024. The past, present and future of printing technology - Preface to the monograph titled *Standards and Energy Saving in Printing Ink Curing and Drying Processes*. *Naturalis Scientias*, 1 (4): 324-327.

DOI: <https://doi.org/10.62252/NSS.2024.1022>. www.naturalisscientias.com

Copyright © 2024 by the author. Published by *Naturalis Scientias*. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License. (<https://creativecommons.org/licenses/by-nc/4.0/>).

Corresponding Author : Zhang, GR, B.Sc., Professor; Email: guoruizhang1960@gmail.com

1. Introduction

Over the past decade, the rapid development of online media has gradually replaced traditional print media, leading to a decline in print volumes for paper publications. However, the demand for commercial printing, such as packaging, labels, and tags, has been steadily increasing. Currently, the prominent changes in China's printing industry are reflected in the following aspects:

- **Diverse substrates:** New packaging and label materials are constantly emerging alongside innovations in products and anti-counterfeiting methods.
- **Increased print volume:** With China's industrial scale expanding globally, product output has surged, resulting in a significant increase in the number of printed materials and necessitating faster printing speeds.
- **Higher quality standards:** As the quality of Chinese industrial products reaches international standards, corresponding printed materials, such as packaging, labels, and instructions, must meet equally high standards.
- **Stricter environmental requirements:** Energy conservation and environmental protection in printing production have become increasingly critical, with green printing standards continuously rising.

These changes collectively demand high-quality and rapid ink drying during high-speed printing, requiring inks to not only dry quickly but also form high-quality, environmentally friendly films. Currently, factors hindering or restricting printing companies from meeting these requirements include issues such as incomplete or improper curing and drying of inks and subpar film formation quality. These issues involve multiple factors, including drying and curing equipment, ink, substrates, plates, ambient temperature and humidity, fountain solutions, printing press roller pressure, dot shapes, mesh structures, and depths.

In late 2023, we conducted research at eight companies involved in printing, ink manufacturing, and composite paper production. We discovered that printing companies often lack a dedicated process department to develop a comprehensive product process before production. Instead, they rely on ink and material suppliers to conduct trial-and-error experiments for each order. Success leads to production, while failure results in order rejection. This fragmented approach to process development makes it impossible to achieve optimal printing results.

Workshop technicians revealed that, to minimize waste and secure bonuses, they are forced to reduce printing speeds, compromising efficiency and consuming more energy.

6. Discussion

Energy conservation and cost reduction are not only environmental imperatives but also crucial factors for reducing printing costs. As printing enterprises scale up and printing speeds increase, especially for UV-cured or thermally dried gravure and flexographic prints, energy consumption has become a significant cost factor. Developing optimal printing processes and establishing standards can help printing machines operate at their best, enhancing competitiveness and profitability. For instance, even a slight decrease in printing speed due to curing and drying issues can proportionally increase equipment and management costs.



During our discussions, we also noted few a shortages of printing professionals in the industry as follows: There are few university graduates specializing in printing, and workshop technicians are predominantly vocational college graduates. Automation in modern printing presses has reduced the demand for technical expertise, as operating these machines now resembles driving smart cars. Previously, operating a press required at least three people, but now one operator and one technician suffice.

Our investigations into ink manufacturers, substrate suppliers, and printing press manufacturers revealed that these companies rarely involve printing process professionals in their design and development. Ink technicians typically specialize in polymers, chemical engineering, or testing, while printing machine technicians come from mechanical and electrical engineering backgrounds. Consequently, product design often fails to consider the intricacies of the printing process, relying instead on basic feedback from printing companies, which is insufficient.

Printing is a highly specialized and complex process. Printing presses, inks, plates, and substrates are all advanced technologies produced by only few countries worldwide. Multiple factors and dynamic interactions involved make achieving ideal print quality a significant challenge. Printed products serve both as industrial applications and works of art, adding endless allure and driving the pursuit of perfection.

China's printing industry has witnessed rapid hardware advancements and substantial volume growth. However, the lag in process technology remains a weakness in enterprise management. Establishing industry standards is essential for industrial upgrading and serves as the "hoop iron" that reinforces the industry's framework.

3. Conclusions

This book, *Standards and Energy Saving in Printing Ink Curing and Drying Processes*, focuses on how to establish standardized ink curing and drying processes. By integrating the factors discussed above into a comprehensive system, it aims to inspire printing process engineers and machine operators to approach process design systematically. Before commencing production, printing companies should develop a thorough process plan through detailed discussions with clients. The finalized process, with its unique characteristics tailored to the specific product, should then be strictly implemented by machine operators.

Additionally, this book serves as a reference for equipment and material suppliers. Suppliers must consider related factors and customer requirements when providing products, rather than relying solely on the demands of printing companies or end customers. Failure to understand the relevant process factors can lead to product defects and associated losses.



About the preface author

Guorui Zhang, Editor-in-Chief, the monograph titled *Standards and Energy Saving in Printing Ink Curing and Drying Processes*. Main contributions to the monograph: Overall framework design and writing. Background and achievements: Former physics teacher and guest professor at Beijing Institute of Graphic Communication; 20 years of research on UV curing and thermal drying processes, along with equipment development; Recipient of the National Science and Technology Progress Award (Third Prize) and four provincial and ministerial science and technology progress awards; Conducted research on surface material modification of substrates and developed printing enterprise management software, earning a ministerial-level award; Published UV Curing Technology in Printing Applications (2006) and Q&A on UV Curing Technology in Printing Applications (2001); Authored numerous articles in printing journals and holds multiple patents.

Data availability

The data that support the findings of this study is available from the author upon reasonable request.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI tools declaration

The author declares that he has not used Artificial Intelligence (AI) tools in the creation of this article.





Original Article

Type and metallogenic series of the cobalt deposits in the East Kunlun, ChinaJZ Yin^{1,2} **Abstract**

Rare metals are increasingly widely and indispensable in modern high-tech fields, making them more and more closely valued by countries around the world. Many countries have included them in the list of critical metals and/or strategic resources for restriction and protection, including cobalt deposits. Mainland China has different rare metal deposits with its 9.6 million square kilometers of land area. This paper summarizes the geological background, industrial category and genetic type of cobalt deposits in the East Kunlun cobalt mineralization province in the northwest of the country, and divides the cobalt deposit metallogenic series. It is hoped that this summary of the East Kunlun cobalt mineralization province in China will help the international economic geology community to compare and study the similarities and differences between Chinese cobalt deposits and similar deposits in other parts of the world, and then find out the metallogenic regularity of global cobalt mineralization, so as to find more cobalt deposits and better serve human society.

Key words: cobalt deposit; the East Kunlun cobalt mineralization province; metallogenic series; genetic type; industrial category; geological setting

Affiliation Info: ¹ Orient Resources Ltd., Canada; ² College of Earth Sciences, Jilin University, Changchun 130061, China

Authors' Contact Info: Yin, JZ: jzyin7@jlu.edu.cn

Citation: JZ Yin. 2024. Type and metallogenic series of the cobalt deposits in the East Kunlun, China. *Naturalis Scientias*, 1 (4): 328-344. DOI: <https://doi.org/10.62252/NSS.2024.1023>. www.naturalisscientias.com

Copyright © 2024 by the author. Published by *Naturalis Scientias*. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License. (<https://creativecommons.org/licenses/by-nc/4.0/>).

Corresponding Author : Yin, JZ, PhD, PGeo, Professor; Email: jzyin7@jlu.edu.cn

1. Introduction

Cobalt is a rare metal and one of the minerals included in the lists of critical metals and/or strategic metals by many countries. Many researchers have discussed and published many articles on its uses, proportions and prices in various industries or fields (Figure 1)¹, so I will not go into details here.

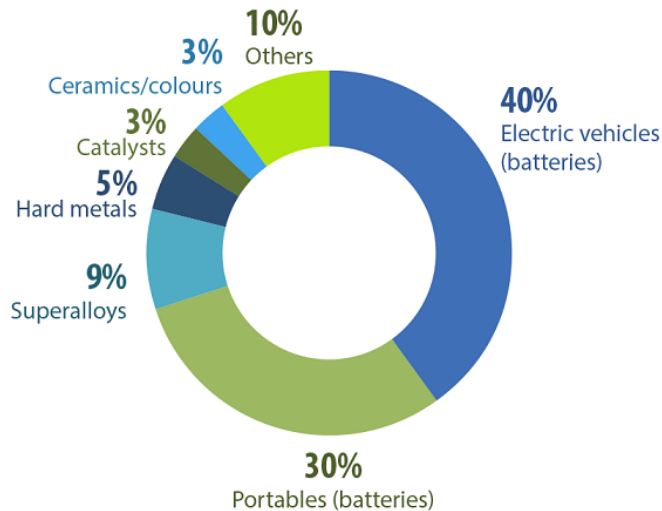


Figure 1. Global uses of cobalt in 2022¹

Due to ideological issues, mainland China is unwilling to provide authentic data on almost all of its important or unimportant minerals. This includes cobalt, which they have included in their list of strategic mineral resources. As a result, the international community knows very little about the true status of the country's cobalt resources, so that there is often no relevant data from the country to compare and reference with the international community.

Fortunately, many geologists in mainland China have not only invested a lot of energy and time in studying the country's cobalt resources, but have also published a considerable number of related research results.

Based on the Chinese research results on cobalt resources published by geologists from mainland China in various domestic journals, this paper proposes the concept of the cobalt mineralization province in East Kunlun, China. Then, by summarizing the geological background of the main cobalt deposits in the area, dissecting the geology of the representative deposits, dividing the genetic types of cobalt deposits, and establishing the metallogenic series of cobalt deposits in the area.

It is hoped that the publication of this article will help the international geological community to discover more similar deposits around the world by studying and comparing the geology of cobalt deposits in mainland China, so as to use these green metal energy to protect the earth's environment and bring a better future to human society.

2. The East Kunlun cobalt mineralization province

The East Kunlun region, located in the northwest of mainland China, is an important polymetallic metallogenic belt in China, including copper, nickel, iron, gold, cobalt and bismuth. So far, the region has produced the Kendeke cobalt-gold-bismuth deposit, Tuolugou cobalt-gold deposit, Mulonggou copper-cobalt deposit and De'erni copper-cobalt deposit from west to east. This region has therefore become one of the most important cobalt mineralization concentration areas in mainland China²⁻⁵.

The eastern Kunlun region, located in the northeast of the Qinghai-Tibet Plateau, the southern edge of the Qaidam Basin, and the western end of the Qinling-Qilianshan-Kunlunshan folded system of the central orogenic belt, has extensive strata exposed (Figure 2a), mainly including Archean and Paleoproterozoic medium-deep metamorphic rock series, Meso-Neoproterozoic shallow metamorphic (volcanic) clastic rocks-carbonate rocks, Ordovician shallow metamorphic clastic rocks intercalated with volcanic rocks and carbonate rocks, Devonian shallow metamorphic clastic rocks-volcanic rocks, and Carboniferous-Permian shallow metamorphic clastic rocks, volcanic rocks and carbonate rocks (Figure 2b). The exposed strata in the Kunbei Belt and Kunzhong Belt are similar, while the strata in the Kunnan Belt are significantly different from those in the Kunbei Belt and Kunzhong Belt.

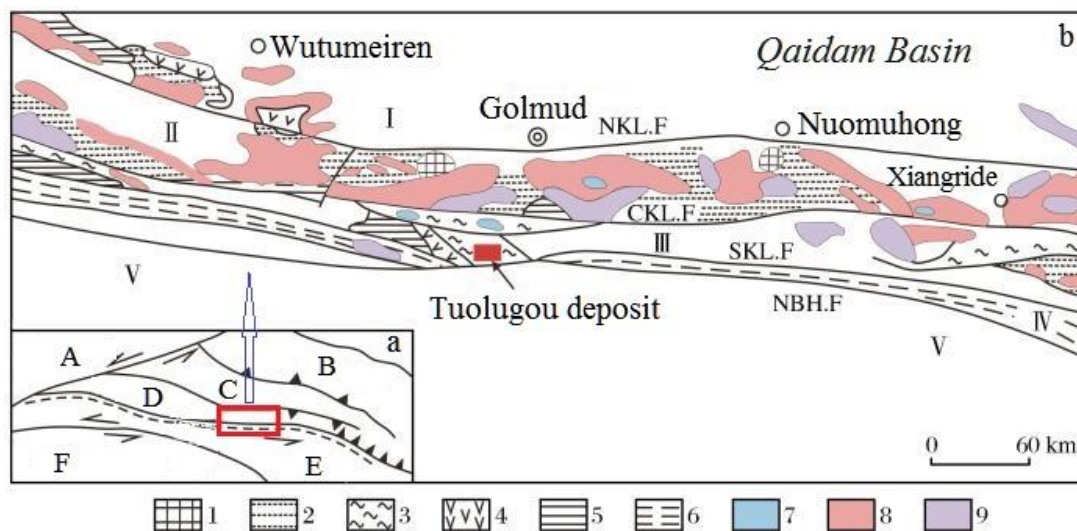


Figure 2. Geology of the east Kunlun region (modified after Wang et al.²)

NKL.F: Kunbei Fault; CKL.F: Kunzhong Fault; SKL.F: Kunnan Fault; NBH.F: North Bayan Har Fault; I: Kunbei Belt; II: Kunzhong Belt; III: Kunnan Belt; IV: Animaqing Belt; V: North Bayan Har Belt. 1. Archean; 2. Mesoproterozoic-Paleoproterozoic; 3. Neoproterozoic; 4. Ordovician; 5. Devonian; 6. Carboniferous-Permian; 7. Pre-Hercynian granite; 8. Hercynian granite; 9. Indosinian granite. A. Altyn fault; B. Qilian Terrane; C. Qaidam Terrane, D. East Kunlun Terrane; E. Bayankala-Songpan-Ganzi terrane; F. Qiangtang Terrane

The East Kunlun orogenic belt, which is generally EW-trending⁶⁻⁷, has experienced the following complex multi-cycle tectonic evolution: the formation of the Proterozoic basement, the evolution of the multi-island ocean in the Early Paleozoic, the Late Paleozoic-Early Mesozoic orogeny, and the Late Mesozoic-Cenozoic orogeny⁸⁻¹⁰. The East Kunlun orogenic belt is further divided into three tectonic units, namely the Kunbei Belt, the Kunzhong Belt and the Kunnan Belt, with

the southern part being the Animaqing Belt and the North Bayan Har Belt (Figure 2b)², with the Kunbei Fault, Kunzhong Fault and Kunnan Fault, which are nearly EW-NWW-trending.

The foliated zones and mylonite zones are developed near the main faults and secondary fault zones of Kunbei, Kunzhong, Kunnan and North Bayan Har, which are generally distributed in a nearly EW direction¹¹. Igneous rocks are well developed in the area, among which the intrusive rocks are mainly intermediate-acidic intrusive rocks of the Hercynian and Indosinian periods, with a small amount of intermediate-acidic rock bodies of the Caledonian period sporadically exposed. The spatial distribution direction of the rock bodies is basically consistent with the regional tectonic line (Figure 2b). Among them, the intermediate-acidic intrusive bodies of the Hercynian period are large in scale and are produced in the form of irregular stocks and batholiths, while the Indosinian intrusive bodies are produced in the form of linear composite batholiths. The volcanic rocks in the area are mainly basic-intermediate-acidic volcanic rocks and pyroclastic rocks, which are mainly produced in the Wanbaogou Group of the Meso-Neoproterozoic, the Nachitai Group of the Ordovician, the Hongshuichuan Formation of the Triassic and the Orlashan Formation.

The metal mineral resources in the area are diverse, mainly jet-sedimentary copper-cobalt-gold-bismuth deposits, ductile shear gold deposits, magmatic copper-nickel-cobalt sulfide deposits, and porphyry-skarn-magmatic hydrothermal iron-copper-lead deposits¹².

There are many cobalt mineralization belts and/or ore fields in the East Kunlun cobalt mineralization province, among which the most representative or typical is the Tuolugou cobalt-gold deposit. This is the first large independent cobalt deposit discovered in the northwest of mainland China (Figure 2). For this reason, this deposit will be introduced in detail below, and other cobalt deposits in the area will be briefly introduced.

3. Examples of cobalt deposits and their brief geology

3.1 Tuolugou Co-Au deposit, Qinghai Province

As the first large-scale independent cobalt deposit discovered in Northwest China, the Tuolugou cobalt-gold deposit is located in the Kunnan fault-fold belt of the East Kunlun folded system. The proven cobalt metal reserves exceed 20,000 tons, with a cobalt grade of 0.06% ~ 0.46%; the gold metal reserves are 4 tons, with a gold grade of $0.45 \times 10^{-6} \sim 5.19 \times 10^{-6}$ ¹³⁻¹⁵。

The Tuolugou cobalt-gold deposit is located in the Kunnan orogenic belt of the East Kunlun orogenic belt, 3 km south of the Kunnan fault zone (Figure 2b). The mining area is generally controlled by a closed compound anticline and a regional shear zone with an axial direction close to EW, and is superimposed with brittle faults after the mineralization period in different directions. The overall trend of the strata in the mining area is close to EW and dips to N. In addition to the Quaternary sediments, the exposed strata are mainly the Nachitai Group of the Ordovician System of the Early Paleozoic Ore-hosting Rocks. This is a set of shallowly metamorphosed greenschist-facies marine volcanoclastic sedimentary rock formations, which are divided into four lithological sections from bottom to top. The second lithological section is carbonaceous phyllite, including spotted carbonaceous phyllite, foliated phyllite, phyllitized slate, mudstone slate and silty slate, followed by met sandstone, met siltstone and a small amount of mudstone limestone. The third lithology section, i.e., the phyllite-schist section, mainly

includes quartz albite with zircon U-Pb age of 468-457 Ma¹⁶, chlorite sericite quartz schist, mylonitized phyllite and mylonite. The fourth lithology section, the sandstone and slate section, includes meta-medium-fine-grained feldspar quartz sandstone, meta-feldspar sandstone, sericite phyllite slate, meta-siltstone and calcareous siltstone, etc.^{5,17}. No intrusive rock bodies are exposed in the mining area.

Cobalt and gold ore bodies are produced in two altered ductile shear zones, the south and the north. The ore bodies in the southern ore zone, located on the south wing of the anticline, are layered and lens-shaped, and are distributed in the third lithological section of the Harabaigou Formation of the Nachitai Group in a nearly EW direction (Figure 3). The ore-hosting rock system is mainly quartz sodium feldspar, chlorite sericite quartz schist and sericite quartz schist. The ore body is controlled by the nearly EW-trending Changzhenggou-Duangou ductile shear zone as a whole, and the ore mylonitization is obvious. The northern ore belt is distributed in the fourth lithological section of the north wing of the anticline in a nearly EW direction and is obviously controlled by faults. Ore types include pyrite ore and specularite-pyrite ore. The ore texture is mainly replacement, automorphic-semiautomorphic granular, anterior granular, etc., and the structure is massive, banded, impregnated, veined and brecciated.

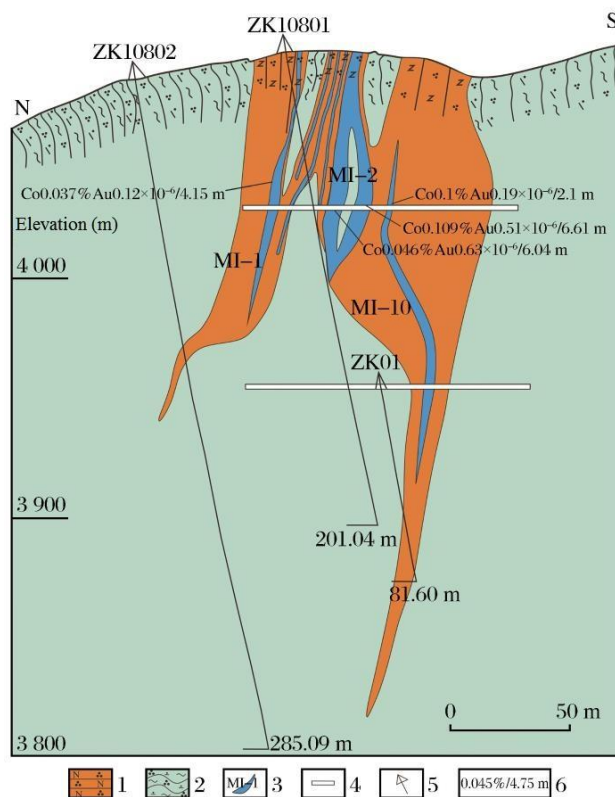


Figure 3. Simplified cross section of #108 exploration line of the Tuolugou deposit (modified after Kui et al.¹⁸)

1. Quartz albite; 2. Chlorite sericite quartz schist; 3. Ore body and number; 4. Adit; 5. Drill hole; 6. Average grade/true thickness body



The ore minerals are mainly pyrite and specularite, followed by cobaltite, nickelite, nickel-cobaltite, chalcopyrite, magnetite, marcasite, pyrrhotite, sphalerite, galena and native gold, etc. The gangue minerals are mainly quartz, albite, carbonate minerals, sericite and chlorite, etc.

The wall rock in the mining area is well altered. The surrounding rock far from the deposit shows propylitization, while the surrounding rock near the ore bodies is mainly silicified, albitization, sericitized, carbonatized and pyritized. Different types of alteration have the characteristics of gradual transition. On the whole, the scale of the ore body is proportional to the intensity of mineralization and alteration¹⁴.

3.2 Kendeke Fe-Co-Bi-Au polymetallic deposit, Qinghai Province

The Kendeke iron-cobalt-bismuth-gold polymetallic deposit is located in the western section of the southern edge of the Qaidam Basin in Qinghai Province, the border area between the Qimantag Mountains in the western section of the East Kunlun Mountains and the Qaidam Basin¹⁹⁻²⁰. Administratively, it belongs to Wutumeiren Township, Golmud City, Qinghai Province, with coordinates: 91°45'30" - 91°46'15" east longitude, 37°00'45" - 37°01'15" north latitude.

The Kendeke iron-cobalt-bismuth-gold polymetallic deposit is located in the Qimantag tectonic mineralization belt in the central volcanic basin of the Qaidam back-arc rift tectonic belt. The ore body is produced in the carbon mud calcium-iron siliceous rock formation of the Upper Ordovician hydrothermal jet deposition, and the stratigraphic and structural control of the ore body is obvious. The deposit is a typical polymetallic composite deposit, and elements such as iron, gold, cobalt, bismuth, lead, zinc, molybdenum and copper can independently constitute the ore body. These ore-forming elements can be either symbiotic or associated, and have a close connection in space. It is generally believed that the Kendeke iron-cobalt-bismuth-gold polymetallic deposit belongs to the hydrothermal jet deposition (reconstruction) type of deposit²⁰. The faults in the area extending in the NW-NWW direction are mainly compressional and compression-torsional. The minerals in the area are mainly produced in the core of the syncline, the turning point of the arc fault and the intersected part of the tectonic belt. The magmatic activity in the area is frequent, with the most developed in the Hercynian period, followed by the Indosinian period. The lithology is well developed from basic to acidic, but acidic rocks are dominant. At present, a total of 35 ore bodies have been identified, including 17 gold ore bodies, 3 cobalt ore bodies, 1 bismuth ore body, 6 gold-cobalt ore bodies, 4 gold-bismuth ore bodies, and 6 gold-cobalt-bismuth ore bodies. The ore bodies are layered, banded and lens-shaped, with a tendency to the N, a dip angle of 25~58 degrees, and generally 30~40°. The ore body is 30~525 m long and 0.82-10.9 m thick, generally 2~5 m thick. Average grade: gold 4.85~15.24 g/t, cobalt 0.06%~0.339%, bismuth 0.761%~2.470%¹⁹⁻²⁰.

The minerals that make up the ore are complex and diverse, mainly including cobaltite, skutterudite, chlorite, molybdenite, chalcopyrite, covellite, pyrite, pyrrhotite, garnet, diopside, quartz and calcite, bismuthinite, natural bismuth, bismuth sulphide, arsenite, epidote, etc.

The ore texture mainly is fine-grained or unequal-grained metamorphic, and skarn minerals are produced in fine-grained or unequal-grained forms. The ore structure has massive, dense massive structure, and banded structure. The natural types of ore can be divided into oxidized ore, mixed ore and primary ore.

3.3 Mulonggou Cu-Co deposit in Qinghai Province

The Mulonggou copper-cobalt deposit is located in the Kunnan orogenic belt between the Kunzhong and Kunnan faults of the East Kunlun orogenic belt. The exposed strata in the mining area are mainly the Mesoproterozoic Wanbaogou Group and the Ordovician-Silurian Nachitai Group. The Mulonggou deposit consists of two zones, the southern and northern ones. The ore bodies are layered and occur at the transition point from volcanic rock to sedimentary rock and are controlled by faults. Therefore, the occurrence is basically consistent with the overall occurrence of the strata in the mining area²¹⁻²⁴. The metamorphic volcanic-sedimentary rock of the Wanbaogou Group, namely the chlorite sericite phyllite (Ph), is the main ore-hosting stratum of the deposit (Figure 4). In addition, the interlayered tuffaceous slate (ZSL) and andesite (α) are exposed in a large area. The cobalt-hosting rocks are mainly chlorite sericite phyllite and carbonaceous slate. The host rock alteration mainly includes sericite, carbonatization and silicification. The magmatic activity in the area has many periods and a long time span, mainly in the Indosinian and Hercynian periods. From early to late, the magmatic activity gradually transitions from intermediate-basic to acidic²¹⁻²².

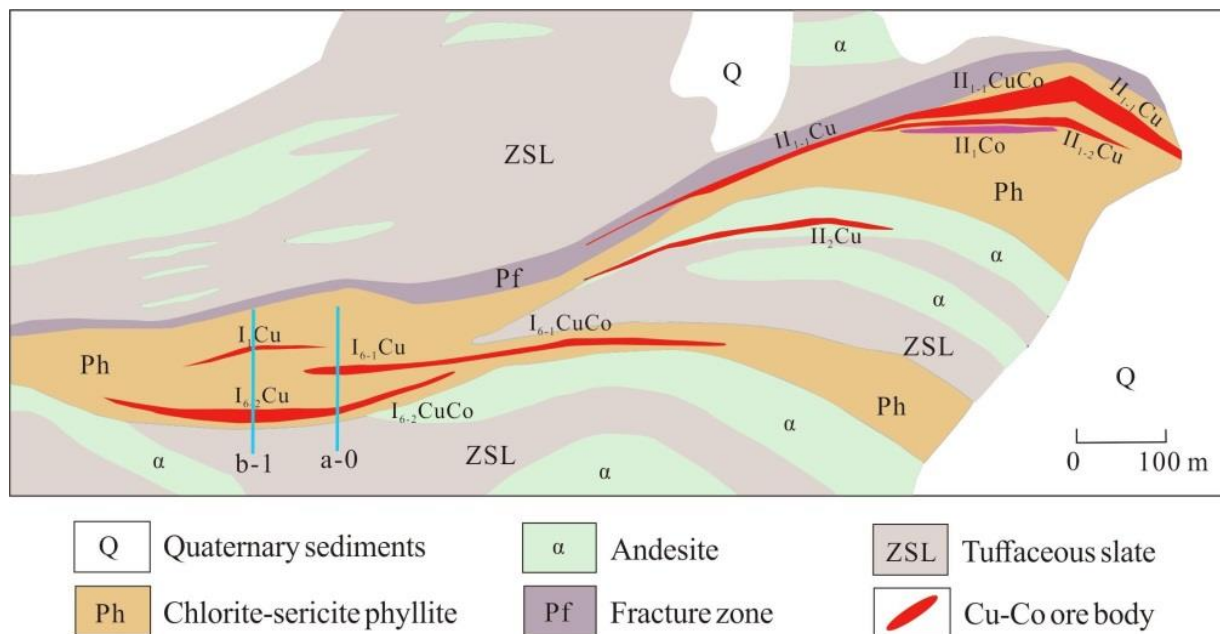


Figure 4. The distribution of the ore body in the northern ore zone of the Mulonggou deposit²⁴

Note: a-0 and b-1 are exploration lines of the Mulonggou deposit

25 ore bodies have been identified in the area, 9 of which are distributed in the southern ore zone and the other 16 are distributed in the northern ore zone. The length of the ore body is between 106 and 335 m and the width is between 2.12 and 13.4 m. Some ore bodies are lens-shaped, some are vein-shaped, and some are quasi-layered. The ore bodies have shrinkage, expansion and branching phenomena. The ore can be divided into sulfide ore with pyrite, chalcopyrite,

bornite and chalcocite as the main mineral combination, oxidized ore with bornite, malachite, chalcocite and azurite as the main mineral combination, and quasi-mixed ore formed by the mixture of the two. The main blocky rich ores such as pyrite, chalcopyrite, chalcocite and bornite show anterior granular structure, and are divided into medium and fine particles. Semi-automorphic-heteromorphic granular structure is common in pyrite and chalcopyrite ores, and the heteromorphic output includes medium-grained and fine-grained covellite, bornite, azurite and malachite, etc. Brecciform, lamellar, veinlet and massive structures are the main ore structures.

3.4 De'erni Cu-Zn-Co deposit in Qinghai Province

The De'erni copper-zinc-cobalt deposit, located in Maqin County, Golog Tibetan Autonomous Prefecture, Qinghai Province, is a polymetallic deposit associated with a variety of useful components such as gold, silver, selenium and gallium. The mass fraction of Cu is 0.41% - 1.64%, Co is 0.053 - 0.17%, and Zn is 0.65% - 7.28%²⁵. The deposit is a large massive sulfide deposit produced in serpentinized harzburgite, dunite and lherzolite in the middle of the Animaqing ophiolite suite in the eastern Kunlun Mountains (Figure 5)²⁵⁻²⁶. The ore is mainly massive and banded copper-bearing pyrite ore. The main ore minerals are pyrite, followed by magnetite, pyrrhotite, chalcopyrite, sphalerite and galena. The ore texture is mainly semi-automorphic granular. Cobalt is relatively enriched in early pyrite, while it is relatively poor in late pyrite²⁶.

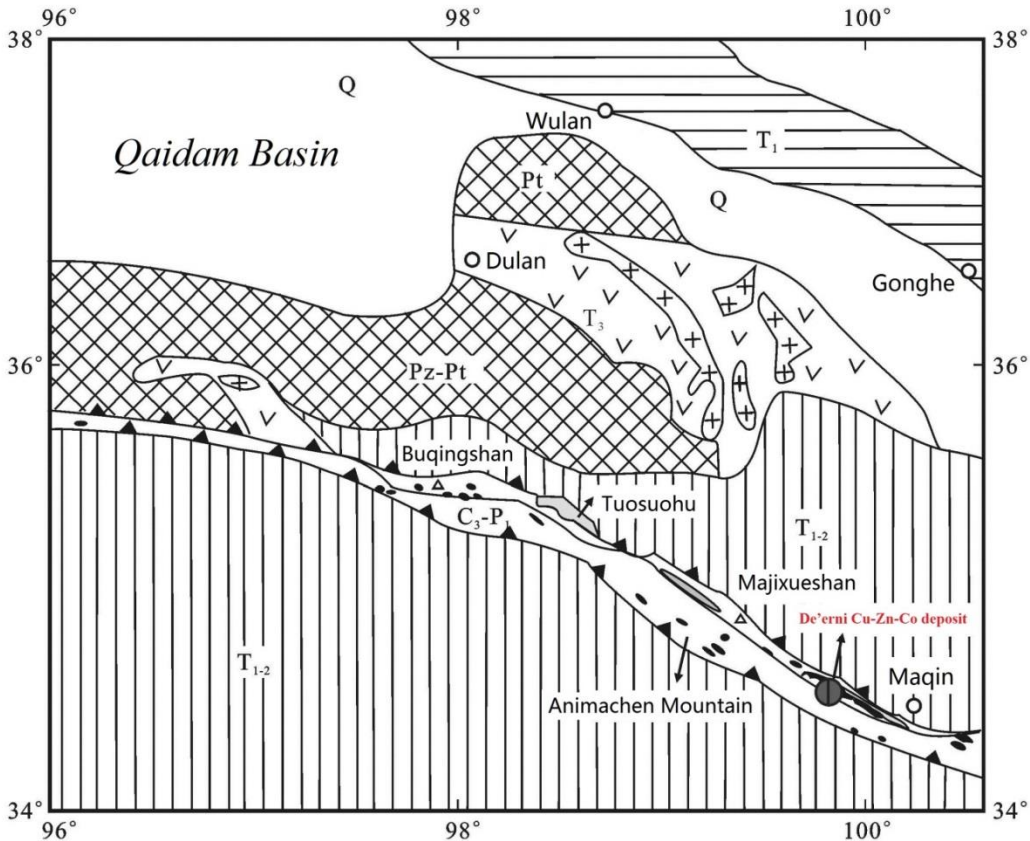


Figure 5. A brief geological map of the Animaqing ophiolite complex²⁷

1. Quaternary slope deposits; 2. Upper Triassic sandstone and slate; 3. Middle and Lower Triassic sandstone and slate; 4. Lower Triassic complex formation; 5. Upper Carboniferous-Lower Permian bioclastic limestone, sandstone and slate, etc.; 6. Carboniferous limestone; 7. Paleozoic-Proterozoic amphibolite and marble; 8. Proterozoic amphibolite and marble; 9. Granodiorite; 10. Ophiolite and copper-cobalt ore bodies; 11. Strike-slip fault; 12. Reverse fault; 13. Town/village

The De'erni copper-zinc-cobalt deposit is located in the middle of the De'erni ophiolite in the eastern section of the Animaqing ophiolite belt (Figure 5). The ophiolite belt is the remnant of the closure of the branch ocean basin of the Paleo-Tethys Ocean. Only the Upper Carboniferous and Lower Permian strata are exposed in the mining area, and the latter is dominant. The De'erni ophiolite is a tectonic block cold intrusion located in a set of shallow marine semi-deep marine bioclastic limestone and sandstone in the Lower Permian. The ophiolite body is consistent with the direction of the regional tectonic line and represents an ancient oceanic crust that has been tectonically dismembered but the rock units are well developed. The ultrabasic rock body where the De'erni copper-zinc-cobalt deposit is located is the largest ultrabasic rock body in the De'erni ophiolite²⁵⁻²⁷, about 17 km long, 200~800m wide and 8~9 km² in area.

The rock mass is NW-SE oriented, inclined to NE, and has a steep dip angle. The rock mass is mainly composed of serpentinized harzburgite, dunite and lherzolite²⁵⁻²⁷. The harzburgite is strongly serpentinized, but the original rock structure is still preserved. The original rock is composed of 75% ~ 90% (volume fraction) olivine, 10% ~ 25% (volume fraction) orthopyroxene and a small amount of chrome spinel. The serpentinized dunite contains a small amount of

orthopyroxene, but still retains the granular structure of the original rock. The dunite and harzburgite are in a gradual transition relationship. The lherzolite is composed of serpentinized olivine, orthopyroxene and relatively fresh monoclinic pyroxene, and contains a small amount of chrome spinel. The volume fraction of fine-grained and evenly distributed monoclinic pyroxene is 5% ~ 10%, mainly diopside.

The De'erni copper-zinc-cobalt deposit is a massive sulfide deposit dominated by copper-bearing pyrite²⁵⁻²⁸. A total of four large-scale industrial ore bodies, namely ore bodies I, II, V and VII, have been identified in the area. Small ore bodies of varying sizes are developed around each main ore bodies. There are 32 in total (Figure 6). The four main ore bodies all extend in a NW-SE direction and lie to the east, but they are layered, or lens-shaped with different elevations. The ore bodies are 60-1040 m long and 17-23 m wide. The proven reserves of copper, cobalt and zinc are 56.7×10^4 , 2.85×10^4 and 14.7×10^4 metric tons, respectively. The main ore bodies are directly hosted in the brecciated carbonated serpentinite and foliated serpentinite of ultrabasic rocks, and the upper part of some main ore bodies is carbonaceous iron siliceous rock about 10 cm thick. The boundary between the ore body and the surrounding rock is clear, and the grade change from the ore body to the surrounding rock is obvious.

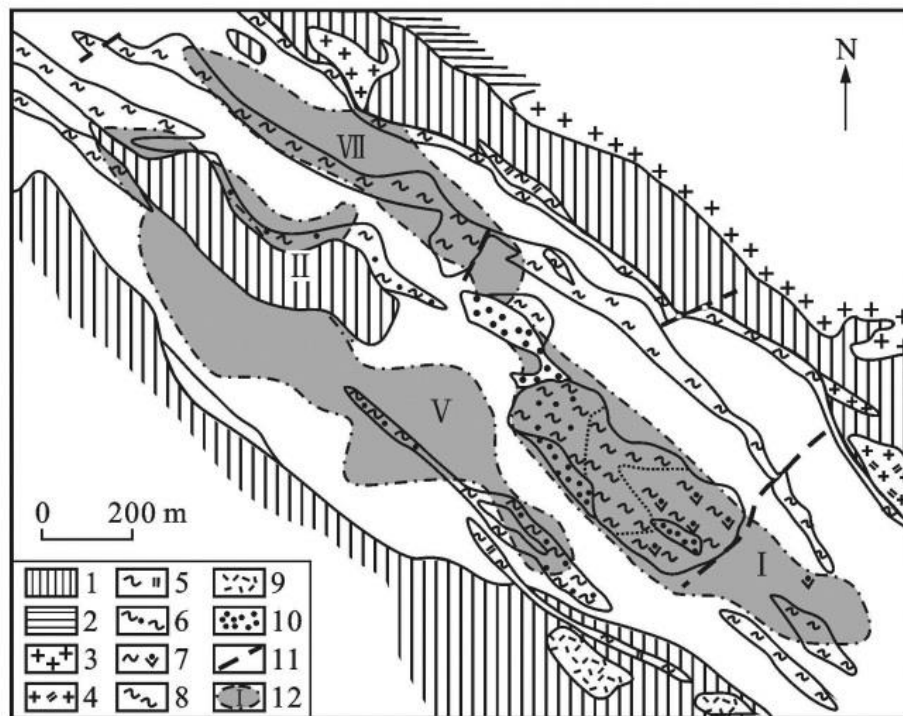


Figure 6. A brief geological map of the De'erni Co-Zn-Co deposit²⁸

1: Lower Permian phyllite carbonaceous slate, phyllite intercalated with sandstone and occasionally met volcanic rock layers; 2: Marble, crystalline limestone intercalated with hornblende schist layers; 3: Granite; 4: Granodiorite; 5: Silicified and carbonated serpentinite; 6: Carbonated brecciated serpentinite; 7: Carbonated serpentinite; 8: Flaky serpentinite; 9: Met andesite; 10: Gossan; 11: Fault; 12: Horizontal projection of ore body and ore body number

The ore bodies of the De'erni copper-zinc-cobalt deposit have obvious chemical zoning²⁵: the upper part is massive and banded pyrite ore with high copper and zinc content, that is, copper-zinc-sulfur ore; the lower part is massive pyrrhotite ore with high copper content, that is, copper-cobalt-sulfur ore. Magnetite is unevenly distributed in the ore body, and its content is generally higher in the lower part of the ore body. At the top of some ore bodies, magnetite appears in veins. The ore structure is mainly massive, impregnated and banded, followed by veins, stockwork, mottled, spotted and brecciated. At the contact between the ore body and the surrounding rock, serpentinization and carbonatization alteration are relatively developed.

4. Origin of cobalt deposits

4.1 Tuolugou Co-Au deposit

Previous researchers have conducted large-scale geochemical, isotope chronology and isotope tracing studies on the Tuolugou Cobalt-Gold Deposit to understand the mineralization geological background, metallogenic age, ore-forming materials and fluid sources of the deposit^{4,13-15,17-18,29}. Based on the major and trace geochemical characteristics of quartz albite, zircon SHRIMP and LA-ICPMS U-Pb ages (468 ~ 457 Ma) and Hf (t) values (-0.61 ~ 12.72), it is believed that the Tuolugou Cobalt-Gold Deposit originated from new crustal materials and was formed in a restricted rift basin on the active continental margin, and was caused by jet deposition far away from the jet vent^{16,29}. Based on the He-Ar-S isotopic characteristics of pyrite ($^3\text{He}/^4\text{He} = 0.10 \sim 0.31 \text{ Ra}$, $^{40}\text{Ar}/^{36}\text{Ar} = 3.02 \sim 569$, $\delta^{34}\text{S} = -4.5\text{‰} \sim +1.5\text{‰}$) and the Re-Os age of pyrite (429 ~ 442 Ma), relevant studies believe that the deposit has undergone hydrothermal jet sedimentation mineralization^{3-15,17,29-30}. Some studies also believe that due to the influence of the Caledonian and Hercynian-Indosinian composite orogeny, regional metamorphism is developed and ductile-brittle structural deformation is strong. Therefore, in addition to the jet sedimentation origin¹⁵, there are also strata-controlled-reformation⁴, hydrothermal deposition-hydrothermal superposition transformation¹⁸ and hydrothermal jet deposition-tectonic transformation, and other genetic view points¹². Some studies also believe that the deposit is based on regional metamorphism, due to the tectonic movement in the region, the existing faults are reopened, and the later medium-low temperature hydrothermal fluids further activate and enrich cobalt and gold along the structural zone to form mineralization³. Some researchers even believe that the deposit was formed in the late Hercynian-Indosinian-Yanshanian period and is a strata-bound-modified independent cobalt-gold deposit related to sodium-rich volcanic rocks. Co and Au were initially enriched in the original sodium-rich intermediate-acidic volcanic rocks and transformed into mineralization through later dynamic metamorphism and deformation⁵.

Based on detailed field geological surveys and petrographic (ore) facies observations, Wang et al. (2023), combined with EPMA and EBSD analysis, divided the mineralization process of Tuolugou cobalt into the jet deposition period and the superposition transformation period². Among them, the jet deposition period formed fine-grained cobalt-rich pyrite (PyI), and the superposition transformation period formed a mineral combination including fine-grained cobalt-rich pyrite (PyII) + arsenic cobaltite-arsenic nickel + sulfide nickel cobalt + pyrrhotite + a small amount of chalcopyrite stage and semi-automorphic-heteromorphic coarse-grained cobalt-poor

pyrite (PyIII) + natural gold. The cobalt content in PyI is 0.38% ~ 4.86%, the cobalt content in PyII is 0.38% ~ 2.74%, and the cobalt content in PyIII is 0.03% ~ 0.58%. PyII often replaces PyI in irregular and ring-shaped forms. Cobalt in the Tuolugou deposit exists in two forms: one is in the form of independent minerals, cobaltite and pyrite, and the other is in the form of isomorphous cobalt-rich pyrite. Exhalative sedimentary mineralization and subsequent structural deformation and superposition are two important processes for the enrichment of cobalt in the Tuolugou deposit.

4.2 Kendeke Fe-Co-Bi-Au polymetallic deposit

The ore bodies of Kendeke Fe-Co-Bi-Au polymetallic deposit are all located in the Tanjianshan Group, which is a set of clastic-volcanic-carbonate rock formations formed in the rift environment of the Late Ordovician. Its clastic rocks are mainly mud-calcium siliceous. The siliceous rocks are banded and worm-like, with obvious thermoplastic deformation characteristics, and are typical hydrothermal sedimentary rocks⁵. This set of hydrothermal sedimentary rocks was altered in the later period to form a set of layered and banded skarns. The distribution of skarns is obviously controlled by the altered fault zone. Obviously, skarns are not caused by contact metasomatism, but are formed by the exchange of calcium, magnesium, aluminum and silicon in mud-calcium siliceous rocks under the action of hydrothermal fluids. The range of hydrothermal action is the range of the altered fault zone¹⁹⁻²⁰.

The formation and evolution of the altered fault zone in the area took a long time and has the characteristics of multi-stage and multi-stage activities. Mineralization is closely related to the altered fault zone.

Kendeke Fe-Co-Bi-Au polymetallic deposit is controlled by submarine hydrothermal sedimentary rocks in the rift environment, brittle-ductile fractures of multi-stage activities, and the geochemical environment unique to carbonaceous strata. Its origin can be attributed to hydrothermal deposition and superimposed transformation.

4.3 Mulonggou Cu-Co deposit

There are several views on the genesis of the Mulonggou copper-cobalt deposit²¹⁻²⁴.

Some people believe that the tectonic background of the Mulonggou mining area is an ocean basin formed in an extensional tectonic environment, and the cobalt mineralization zone is obviously controlled by strata and faults. The late Paleozoic island arc environment is the main geological environment for the formation of the Mulonggou copper-cobalt deposit²¹.

Some studies have also shown that the Mulonggou copper-cobalt deposit is a superimposed and transformed VHMS-type deposit. The lead isotope of chalcopyrite shows that the ore-forming materials of the Mulonggou copper-cobalt deposit come from a deeper source, and the relatively developed fault structure in the area provides good conditions for the formation of this VHMS-type copper-cobalt deposit²².

Other studies have suggested that graphite-rich carbonaceous slates are developed near the rich ore bodies of the Mulonggou copper-cobalt deposit, so mineralization is closely related to carbonaceous slates.

Some people also believe that the ore of the deposit has a laminar structure equivalent to sedimentary structures, and the siliceous rocks distributed along the ore bodies are typical exhalative sedimentary rocks, so the mineralization is caused by syngenetic sedimentary hydrothermal fluids. Of course, some people believe that the Mulonggou copper-cobalt deposit is a late hydrothermal deposit.

Other researchers have proved that the Mulonggou copper-cobalt deposit is a submarine exhalative sedimentary deposit (SEDEX) based on the geological, geochemical and isotopic chronology research results of the deposit²⁴.

Other researchers have concluded that the Mulonggou copper-cobalt deposit was formed in the Carboniferous-Early Permian period and has successively experienced three stages: the hydrothermal exhalative sedimentary mineralization period, the structural deformation superposition transformation mineralization period and the surface period.

4.4 De'erni Cu-Zn-Co deposit

The mineralization age of De'erni Cu-Zn-Co deposit is 295.5 ± 7.2 Ma²⁶, which is significantly earlier than the Indosinian granite in the north of the mining area. No signs of hydrothermal activity such as thick quartz veins or carbonate veins were found in the area. This excludes the possibility that the formation of the deposit is related to the Indosinian granite.

In addition, the ore minerals of the De'erni deposit are enriched in chalcopyrite and pyrite, formed in a medium-temperature environment, and is mainly blocky and banded ores. This is obviously different from the magma liquation deposit. The latter is mainly composed of chalcopyrite, pentlandite, and pyrrhotite, mainly impregnated ores, and the main mineralization temperature is high.

Compared with massive sulfide deposits around the world, the De'erni Cu-Zn-Co deposit is similar to the tectonic setting and mineral assemblage of Cyprus-type massive sulfide deposits²⁶. The trace element content of its early pyrite, chalcopyrite and pyrrhotite is more similar to that of VMS-type deposits³¹.

Compared with the metal mineral composition of magmatic hydrothermal deposits, sphalerite in the De'erni Cu-Zn-Co deposit is richer in Fe and poorer in Cd and Bi²⁶ than sphalerite in the Balipo molybdenum deposit in Shaanxi Province, China. The cobalt content in pyrite is also higher than those in general hydrothermal deposits.

Therefore, the origin of the De'erni Cu-Zn-Co deposit is different from that of general hydrothermal deposits and magmatic deposits, and is more similar to that of Cyprus-type massive sulfide deposits³².

In recent years, more and more studies have shown that the deposit belongs to the submarine jet sedimentary type. Specific evidence includes: the presence of carbon-containing iron siliceous rocks with hydrothermal deposition in the surrounding rocks adjacent to the ore body³³; the newly discovered "strawberry-shaped" pyrite with submarine jet deposition; the widespread

development of sedimentary structural features such as brecciated, lamellar, and banded structures³⁴. The carbonate + quartz + barite + gypsum mineral assemblage was discovered³⁵. The sulfur isotope composition $\delta^{34}\text{S}$ is $(-6.15 \sim 11.45) \times 10^{-3}$, with an average of 6.37×10^{-3} . It shows that it mainly comes from seawater, and a small part is related to hydrothermal action. The oxygen isotope composition of calcite in the ore $\delta^{18}\text{O}$ is $(11.32 \sim 12.98) \times 10^{-3}$. It further shows that the seawater and hot water in the basalt fissures on the ocean floor were mixed during the formation of the deposit³⁶. The carbon isotopic compositions of gangue minerals quartz and calcite are $(15 \sim 45) \times 10^{-3}$ and $(-2.013 \sim 3.83) \times 10^{-3}$, respectively, which are characteristic of marine sedimentary carbonate³⁷.

5. Deposit type and metallogenic series

As a copper-loving and iron-loving element, cobalt tends to be enriched in the mantle. Various geological processes such as laterite weathering, diagenesis, magma and hydrothermal activities can lead to local enrichment of cobalt in the crust. This geochemical property of cobalt determines that its output is closely related to traditional bulk minerals such as copper, iron, nickel and zinc.

This is indeed the case. At present, the world's cobalt mainly comes from (meta) sedimentary copper-cobalt deposits (60%), copper-nickel sulfide deposits related to ultrabasic-basic rocks (23%) and laterite-type nickel-cobalt deposits (15%)²³⁻²⁵. Except for a few independent cobalt deposits such as the Bou Azzer cobalt-nickel-arsenic-gold-silver deposit in Morocco and the above-mentioned Tuolugou Co-Au deposit, the vast majority of cobalt metal in the world is associated and/or symbiotic with copper, copper-nickel, copper-gold, copper-iron, nickel-silver-arsenic-bismuth, etc., and appears as a by-product. Independent industrial cobalt deposits are relatively rare.

Based on the previous research results on the known cobalt deposits in the East Kunlun orogenic belt, the industrial category and genetic types of the cobalt deposits in this area are summarized in the following table:

Table 1. Industrial category and genetic type of the cobalt deposits in the east Kunlun region, China

Industrial category	Genetic type	Co-bearing mineral/ore type	Representative deposit
Independent	Sedimentary modification & hydrothermal superposition	Cobaltite, siegenite, pyrite	Tuolugou Co-Au deposit
Associated	Hot water deposition-superimposition transformation	Cobaltite, Skutterudite, erythrite	Kendeke Fe-Co-Bi-Au polymetallic deposit
		Au-Co-Bi	
		Au-Bi-Co	
		Co	
		Mo-Co	
	Fe-Co-Bi-Au polymetallic		
	SEDEX or VHMS overlay transformation	Cobaltite, siegenite, glaucodot	Dulengou Cu-Co deposit
Seafloor jet deposition	Pyrite, Cu-Co-S	De'ermi Cu-Zn-Co deposit	
Porphyry Cu-Co	To be discovered	To be discovered	
Porphyry Cu-Ni-Co			
Porphyry Cu-Mo-Co			
Porphyry Mo-Cu-Co			

According to the above-mentioned known cobalt deposits, the East Kunlun cobalt mineralization province has the following metallogenic series:

- Cobalt-gold series
- Fe-Co-Bi-Au series
- Copper-cobalt series
- Cobalt-bismuth series

It is predicted that in the near future, the East Kunlun cobalt mineralization province will discover the following new metallogenic series:

- Magmatic Ni-Co series
- Cu-Ni-Co series
- Hydrothermal series
- Volcanogenic cobalt polymetallic series
- Cobalt-Bismuth-Gold series.

6. Conclusions

The complex and diverse geological background and the very active multi-stage orogenic movement have created a variety of metallogenic types and mineral series in the cobalt deposits in the East Kunlun orogenic belt of mainland China.

There is every reason to believe that with the deepening and expansion of mineral exploration and geological survey, more new types of cobalt mineralization will be discovered in this area. Such as nickel-cobalt, copper-nickel-cobalt, molybdenum-cobalt related to magmatic activity, and skarn-type cobalt polymetallic mineralization related to skarnization.

In short, East Kunlun is a cobalt province that is closely related to cobalt and has unlimited possibilities to develop new types of cobalt deposits.

7. References

1. Government of Canada. <https://natural-resources.canada.ca/minerals-mining/mining-data-statistics-and-analysis/minerals-metals-facts/cobalt-facts/24981>. Retrieved January 6, 2025.
2. Wang ZL, Zhang K, Xu DR, Zou SH & Wang YF. 2023. Mineralogical fingerprints of Co metallogenesis in the Tuolugou deposit · East Kunlun Orogen. *Gold Science and Technology*, 31 (2): 175-189. DOI:10.11872/j.issn.1005-2518.2023.02.121.
3. Li LY, Xu CS & Chen JZ. 2005. A preliminary study on the geological characteristics and genesis of the Tuolugou cobalt-gold deposit. *Chinese Journal of Engineering Science*, (S1): 6. DOI: CNKI:SUN:GCKX.0.2005-04-068.
4. Li HM, Shen YC, Hu ZG, Qian ZZ, Liu JQ, Sun JD. 2001. A preliminary study on the geological characteristics and genesis of the Tuolugou cobalt (gold) deposit in East Kunlun, Qinghai. *Geology and Exploration*, 37 (1): 60-64. DOI: 10.3969/j.issn.0495-5331.2001.01.014.

5. Li HM, Shen YC & Hu ZG. 2000. Geological characteristics of the Tuolugou cobalt (gold) deposit in East Kunlun, Qinghai Province: a new type of cobalt (gold) deposit associated with sodium-rich volcanic rocks. *Bulletin of Mineralogy, Petrology and Geochemistry*, (4): 321-322.
6. Jian X, Weislogel A, Pullen A et al. 2020. Formation and evolution of the Eastern Kunlun Range, northern Tibet: Evidence from detrital zircon U-Pb geochronology and Hf isotopes. *Gondwana Research*, 83: 63-79.
7. Dong Y, Sun S, Santosh M et al. 2021. Central China orogenic belt and amalgamation of East Asian continents. *Gondwana Research*, 100: 131-194.
8. Pan Y, Zhou W, Xu R et al. 1996. Early Paleozoic geological features and evolution of the Kunlun Mountains. *Science in China (Series D)*, 26 (4): 302-307.
9. Zhu YH. 2002. *Ophiolite Magmatic Rocks and Tectonic-Magmatic Evolution in the East Kunlun Composite Orogenic Belt*. Wuhan: China University of Geosciences Press.
10. Liu YL, Zhang AK, Liu ZG et al. 2022. Genetic types and mineralization models of gold deposits in the western section of East Kunlun, Qinghai. *Gold Science and Technology*, 30 (4): 483-497.
11. Pan T. 2005. Study on the Metallogenic Series of Cobalt Deposits in Eastern Kunlun Orogenic Belt. Dissertation, Changchun: Jilin University.
12. Zhang AK, Wang JJ, Liu GG et al. 2021. Main metallogenic genetic series in the Qimantag area, Qinghai Province and their metallogenic models. *Acta Mineralogica Sinica*, 41 (1): 1-22.
13. Feng CY, Zhang DQ, Qu WJ et al. 2006a. Re-Os isotopic dating of pyrite in the Tuolugou SEDEX cobalt (gold) deposit, Golmud, Qinghai Province. *Acta Geologica Sinica*, 80 (4): 571-576.
14. Feng CY, Zhang DQ, She HQ et al. 2006b. Tectonic setting and metallogenic mechanism of Tuolugou cobalt (gold) deposit, Qinghai Province. *Mineral Deposits*, 25 (5): 544-561.
15. Feng CY, Qu WJ, Zhang DQ et al. 2009. Re-Os dating of pyrite from the Tuolugou stratabound Co (Au) deposit, eastern Kunlun orogenic belt, northwestern China. *Ore Geology Reviews*, 36: 213-220.
16. Feng CY, Zhang DD, Dang XY et al. 2005. SHRIMP zircon U-Pb dating of quartz albite from the Tuolugou cobalt (gold) deposit, Golmud, Qinghai, China - constraints on the age of the Naj Tal group. *Geological Bulletin of China*, 24 (6): 501-505.
17. Zhang DQ, She HQ, Xu WY et al. 2002a. Geochemical constraint on the metallogenetic geological background and genesis of Tuolugou sedimentary-exhalative cobalt-gold deposit. *Acta Geoscientica Sinica*, 23 (6): 527-534.
18. Kui MJ, Zhang AK, Liu YL, et al. 2019. Geological characteristics and prospecting model of the Tuolugou cobalt deposit in Qinghai. *Mineral Exploration*, 10 (1): 57-64.
19. Yi YC, Jiao GJ & Zhang FY. 2006. Characteristics of the Kendeke iron-cobalt polymetallic deposit in East Kunlun, Qinghai. *Geology and Exploration*, 42 (3): 30-35.
20. Pan T & Sun FY. 2003. Mineralization characteristics and prospecting direction of the Kendeke Cobalt-Bismuth-Gold Deposit in East Kunlun, Qinghai. *Geology and Exploration*, 39 (1): 18-22.
21. Yao WG, Jia QZ, Zhang HW & Yang ZG. 2002. Geological characteristics and genesis of the Dulenggou copper-cobalt deposit in Qinghai. *Mineral deposit geology*, (S1): 4. DOI: CNKI:SUN:KCDZ.0.2002-S1-143.
22. Wang CY, Qi HW, Zhang HB & Ju SF. 2018. Geological characteristics and mineralization conditions of the Mulonggou copper-cobalt deposit in Qinghai. *China Manganese Industry*, 36 (3): 4. DOI: CNKI:SUN:ZGMM.0.2018-03-015.
23. Li H, Jiang SY, Li SJ, Su HM, Dong JX, Li YB & Chen XL. 2023. Geological characteristics, genetic mechanism and prospecting indicators of magmatic nickel-cobalt deposits in the eastern Kunlun orogenic belt. *Acta Petrologica Sinica*, 39 (4): 1041-1060. DOI: 10.18654/1000-0569/2023.04.07.
24. Wang W, Jiang SY, Chen ZP, Su HM, Li H & He SY, 2024. The origin and mineralization processes of the Mulonggou copper-cobalt deposit in the East Kunlun orogenic belt, western China. *Ore Geology Reviews*, 171. DOI: <https://doi.org/10.1016/j.oregeorev.2024.106186>.



25. Duan J, Qian ZZ, Huang XF, Dong FQ, Zhao XJ & Lu H. 2014. Ore mineral characteristics and geological significance of the Heydarni copper (cobalt) deposit. *Journal of Earth Sciences and Environment*, 36 (1): 201-209.
26. Jiao JG, Lu H, Sun YL, Huang XF & Duan JQ. 2013. Re-Os dating for De'erni Cu (Zn-Co) ore deposit in Qinghai Province, China and its geological implication. *Geoscience*, 27 (3): 577-584. DOI: 10.3969/j.issn.1000-8527.2013.03.008.
27. Yang JS, Shi RD, Wu CL et al. 2009. Dur'ngoi ophiolite in east Kunlun, northeast Tibetan Plateau: evidence for Paleo Tethyan Suture in northwest China · *Journal of Earth Science*, 20 (2): 303-331.
28. Song ZB, Li YZ, Chen XY et al · 2012. Discovery of exhalative rock - ferro-siliceous rock in the De'erni copper deposit of East Kunlun Mountains and its metallogenic significance · *Geological Bulletin of China*, 31 (7): 1170-1177.
29. Zhang DQ, Wang Y, Feng CY et al. 2002b. Geology and geochemistry of Tuolugou exhalative-sedimentary Co-Au deposit, Qinghai Province. *Mineral Deposits* · 21 (3): 213-222.
30. Zhu HP. 2005. Geological characteristics and prospecting potential evaluation of the Tuolugou cobalt deposit in Qinghai Province. Dissertation, Changchun: Jilin University.
31. Hawley JE & Nichold I. 1961. Trace elements in pyrite, pyrrhotite and chalcopyrite ores · *Economic Geology*, 56 (3): 467-487.
32. Dergachev AL, Eremin NI & Sergeeva NE. 2010. Volcanogenic massive sulfide deposits of ophiolite associations · *Moscow University Geology Bulletin*, 65 (5): 265-272.
33. Song ZB, Chen XY, Ren YX et al. 2008. Petroregimentation, petrochemistry and geologic meaning of "Carbonaceous (Gritstone) slabstone" in De'erni deposit, Eastern Kunlun area, Northwest China · *Northwestern Geology*, 41 (4): 77-81.
34. Jiao JG, Huang XF, Yuan HC et al. 2009 · Progress in the research of De'erni Cu (Co) ore deposit · *Journal of Earth Sciences and Environment*, 31 (1): 42-47.
35. Dong FQ. 2010 · Study on the mineralization stages and ore genesis of the De'erni copper deposit · Dissertation, Xi'an: Chang'an University.
36. Wang YW & Qin KZ. 1997. The extremely basic member of VAMSD deposit series - the De'erni large copper - cobalt deposit of Qinghai Province: its geological characteristics and genetic type · *Mineral Deposits*, 16 (1): 1-10.
37. A YS. 2001. New recognition on the origin of De'erni sulfide deposit in Qinghai Province · *Qinghai Geology*, 1 (1): 40-44.

Data availability

The data that support the findings of this study is available from the author upon reasonable request.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI tools declaration

The author declares that he has not used Artificial Intelligence (AI) tools in the creation of this article.





Book Review

Finally, the complete eight-volume Collected Works of Chia Yung Hsieh is published

JZ Yin^{1,2,3}

Abstract

This article introduces the main content of the *Collected Works of Chia Yung Hsieh*, which took nearly 20 years to be fully published, and the difficult process and twists and turns behind it that are unknown to the public. On the surface, this long publishing process is a funding issue, but in fact it is a political ecology or political orientation issue. To be precise, it is a major issue of how to evaluate the real contributions of historical figures in a realistic way.

Key words: Chia Yung Hsieh; Collected Works of Chia Yung Hsieh; a pioneering geologist in China; after many twists and turns; Lisheng Zhang

Affiliation Info: ¹ College of Earth Sciences, Jilin University, Changchun 130061, China; ² Wuhan Institute of Technology, Wuhan 430205, China; ³ Orient Resources Ltd., Canada

Authors' Contact Info: Yin, JZ: jzyin7@jlu.edu.cn

Citation: Yin, JZ. 2024. Finally, the complete eight-volume Collected Works of Chia Yung Hsieh is published. *Naturalis Scientias*, 1 (4): 345-363. DOI: <https://doi.org/10.62252/NSS.2024.1024>.

Copyright © 2024 by the authors. Published by *Naturalis Scientias*. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License. (<https://creativecommons.org/licenses/by-nc/4.0/>).

Corresponding Author : Yin, JZ, PhD, PGeo, Professor; Email: jzyin7@jlu.edu.cn

1. Introduction

The author of this article has published a long book review, *A complete chronicle of Chia Yung Hsieh (C. Y. Hsieh) and his life and works*, in the third issue of the international English journal *Naturalis Scientias* in 2024. *A complete chronicle of Chia Yung Hsieh* has provided a detailed and objective introduction to Mr. Chia Yung Hsieh (hereinafter referred to as Hsieh), one of the great founders of China's geological sciences, his unique and great contributions to China's geological cause, his path to studying geology, and his numerous "China's firsts" and some "world's firsts" in many fields of earth sciences. Readers who want to know the details of the above article, please log in and read through the following link of the above article: Yin, JZ. 2024. A complete chronicle of Chia Yung Hsieh (C. Y. Hsieh) and his life and works. *Naturalis Scientias*, 1 (3): 260-285. DOI: <https://doi.org/10.62252/NSS.2024.1019>.

Mr. Hsieh's great contribution to the earth sciences of China and the world is not only in the field of various geological science theories, but also in the field of mineral exploration. His contributions have not yet been matched by any other geologist in China or even in the world.

As soon as the above article of the author of this article came out, another good news came: the eight-volume *Collected Works of Chia Yung Hsieh* was finally published (Figure 1).

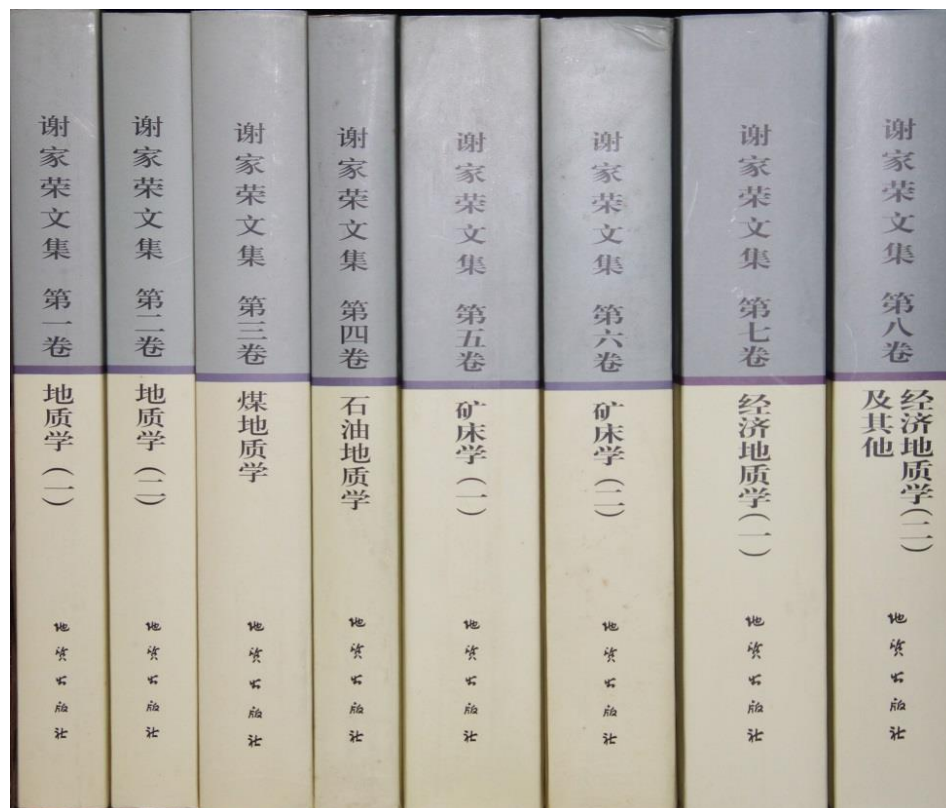


Figure 1. The complete version of the *Collected Works of Chia Yung Hsieh*, which was finally released after 20 years

The author of this article has therefore struck while the iron is hot, and with the strong support of Professor Lisheng Zhang (hereinafter referred to as Prof. Zhang), the executive editor of *Collected Works of Chia Yung Hsieh*, now gives a relatively detailed introduction to the

publication of this collection of works. It is hoped that it will help readers who are interested in understanding Mr. Hsieh's academic thoughts and related creations to deepen their understanding through further reading of his works, and then promote his academic thoughts through publicity.

2. About Chia Yung Hsieh

It is necessary to briefly introduce Mr. Hsieh's life story to refresh everyone's memory and cognition of him.

Professor Hsieh (1897-1966), a well-known geologist and late academician of the Chinese Academy of Sciences, was once the vice chairman of the China Geological Work Planning Steering Committee and director of the Planning Department, the engineer-in-chief of the Ministry of Geology, and the standing committee member and the engineer-in-chief of the Reconnaissance Committee of the Ministry of Geology.

Hsieh is recognized an all-round geologist. The breadth and depth of his research in the field of geology are unique in the Chinese geological community, and he is the first and pioneer in many aspects. Among them, his attainments in mineral deposits (including coal petrology, mineralogy, coalfield geology, and petroleum geology) are the deepest. Hsieh is the geologist who has discovered the most mineral deposits in China so far. He was the first to propose that China's oil is not limited to the northwest, and actively advocated the general search for oil throughout the whole country. He was also one of the first geologists to notice the search for oil in the Northeast Plain.

Hsieh formulated the strategic policy of "conducting large-scale and comprehensive geological survey in oil-bearing and potential oil-bearing areas throughout the country" for China's oil reconnaissance in the 1950s. At the same time, he pointed out the correct tactical policy of "determining oil reservoirs and studying trap structure types, which is particularly critical in China where oil exploration has just begun", and advocated that "in order to achieve the reserves required by the second five-year plan, several large new oil fields must be discovered. In order to enable some new oil fields to be put into production and obtain output within this period, we must not only work in the proven oil fields in the vast northwest region, but also accelerate exploration in areas with convenient transportation and easier development, so as to achieve twice the result with half the effort". Hsieh prepared the ideological and theoretical basis for the eastward shift of China's oil exploration strategy, and made significant contributions to the eastward shift of China's oil reconnaissance and exploration strategy, especially to the discovery of the Daqing Oilfield, North China Oilfield and Bohai Bay Oilfield.

Professor Hsieh is also known for his diligence in writing. He completed nearly 500 geological works in his lifetime, many of which still have important theoretical and practical significance.

3. Summary of the Collected Works of Chia Yung Hsieh

In 2005, the *Collected Works of Chia Yung Hsieh* Editorial Committee was established to commemorate the 110th anniversary of Chia Yung Hsieh's birth, and plans were made to publish an eight-volume edition of the *Collected Works of Chia Yung Hsieh*. The Editorial Committee is composed of Academician Xuejing Xie and Prof. Zhang as Chief Editors, and Professors Zhang, Yuntang Pan and Tingyu Chen as Executive Editors. A total of 30 academicians of the Chinese Academy of Sciences and the Chinese Academy of Engineering serve as consultants. In the same year, the State Administration of Press, Publication, Radio, Film and Television of China



included the *Collected Works of Chia Yung Hsieh* in the list of key national planning books during the 11th Five-Year Plan period. The *Collected Works of Professor Hsieh* consists of eight volumes, and the key contents of each volume are as follows:

- Volumes 1 and 2: Geology
- Volume 3: Coal Geology
- Volume 4: Petroleum Geology
- Volumes 5 and 6: Mineral Deposits
- Volume 7: Economic Geology
- Volume 8: Economic Geology and Others

Through the efforts of the editorial committee, the first to fourth volumes of *Collected Works of Chia Yung Hsieh* were published by Geological Publishing House in Beijing from January 2007 to August 2008, and the fifth and sixth volumes were published in July 2011. Later, due to the death of the original editor Junzhong Chen and mainly due to the lack of publishing funds, the publication of the seventh and eighth volumes was delayed for a long time. It was not until August 2020 when the four siblings Dr. Yuanhong Xie, Yuanru Xie, Yuanquan Xie, and Yuanjie Xie, the eldest grandchildren of Professor Hsieh, raised 200,000 CNY and remitted it to the publishing house, it was restarted and finally completed in December 2024.

The eight-volume *Collected Works of Chia Yung Hsieh* includes 457 pieces of Mr. Hsieh's works that have been collected so far, totaling about 7.6 million Chinese characters. The main contents of each volume are as follows:

3.1. Volume 1

The first volume contains 32 articles (books) written by Professor Hsieh between 1915 and 1925 which are the important documents for the early development of modern Chinese geology (Figure 2).

Among them are the *Gansu Earthquake Report in December of the 9th Year of the Republic of China* and *Earthquake Situation in Gansu and Other Provinces in December of the 9th Year of the Republic of China* which are one of the earliest classic documents for earthquake research in modern China and are valuable historical documents that record the great Haiyuan earthquake in Gansu in the early 20th century. There are *Preliminary Notes on the Composition and Structure of the First Specimen of Meteoric Stone Received by the Geological Survey of China*, *Study of Chinese Meteorites* and *A Brief Talk on Meteorites* which pioneered the study of modern meteorites in China. There is *Geology (Part 1)*, the first general geology textbook written and published by Chinese people. There is also *Geological Structure and Physiographic history of the Yangtze Valley Below Wushan*, an important work on Chinese geology and geomorphology co-authored by Hsieh and L. F. Yih, as well as many investigation reports and/or papers on Hubei geology written by Professor Hsieh when he was engaged in Hubei geological survey in his early years.

All these works not only bear witness to the early development history of Chinese geology, but also have important guiding significance for China's geological research today.

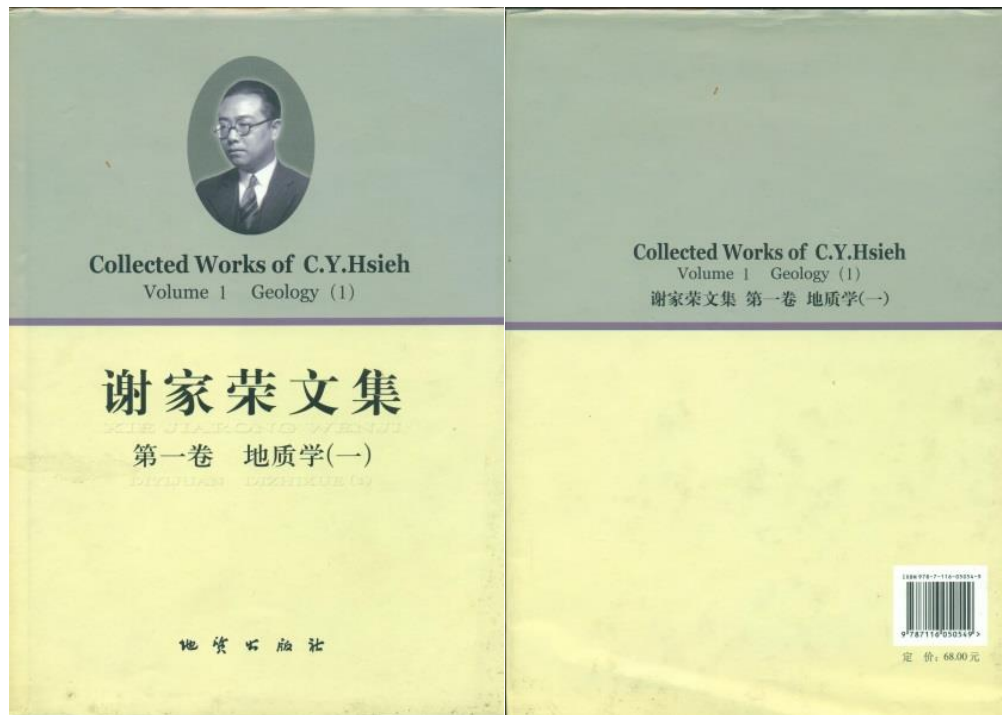


Figure 2. Front & back covers of the first volume of *Collected Works of Chia Yung Hsieh*

3.2. Volume 2

This volume contains 59 works written by Professor Hsieh between 1928 and 1963 (Figure 3). Among them are a series of articles on hydrogeology of Nanjing water supply completed by him in the late 1920s and early 1930s which pioneered the solution of urban water supply hydrogeology by Chinese geologists, the first batch of Chinese soil survey papers, such as *Soil Classification and Soil Survey (Introductory Note on the Significance of the Soil Survey)* and *Soil Reconnaissance in San-ho, Ping-ku and Chi-Hsien Area* published in 1931, important works on Chinese geology and geomorphology, such as *Note on the Geomorphology of the North Shensi Basin* and *Overview of Chinese Physiographic Periods* published in 1933-1934, important papers on the geology of Xishan, Beijing, such as *New Research on Geology of the Western Hills* and *An outline of the Geological Structure of the Western Hills of Peiping* (in English) published from 1933 to 1937 and important papers on the study of Chinese geotectonics in his later years, such as *On the Geotectonic Framework of China* and *Major Geotectonic Features of Southeast China* (in English). In addition, this volume also published for the first time the first chapter of his unfinished newly compiled *Geology of the Western Hills of Peiping*, *Stratigraphic System of the Western Hills of Peiping* and papers such as *Preliminary Observation of the Landslide Phenomenon in the South Wall of the West Open-pit Mine of the Fushun Mining Bureau* written by Mr. Mengxiong Chen under the guidance of Prof. Hsieh in studying the landslide in the open-pit mine of the Fushun Coal Mine in Liaoning Province, China in 1953.

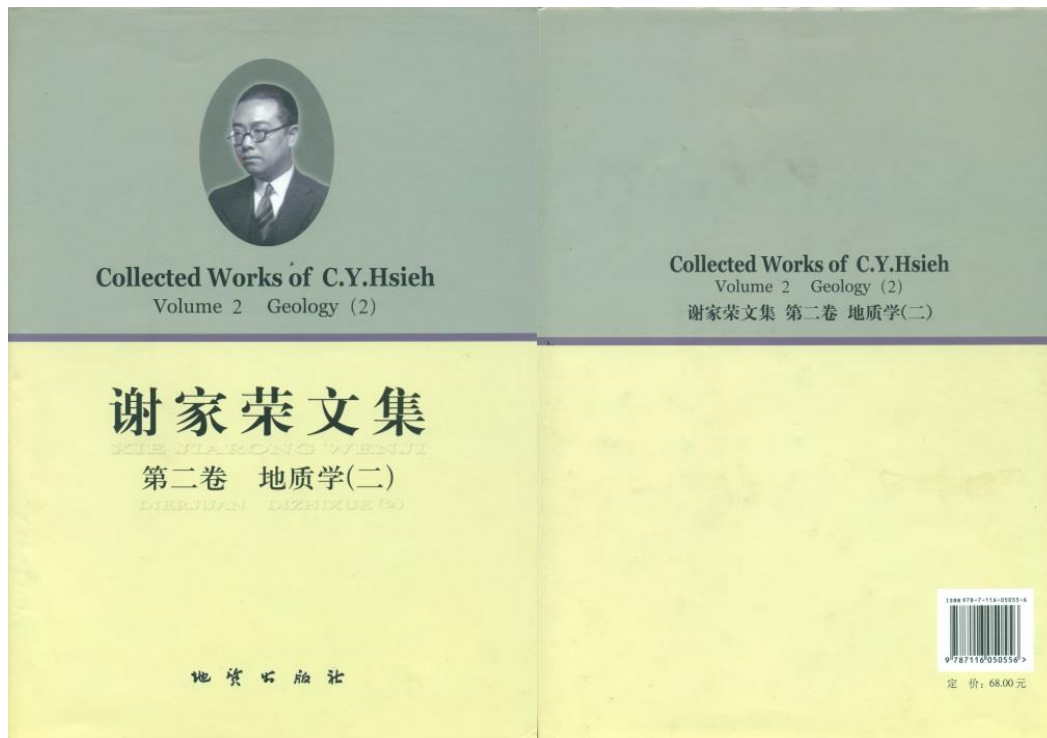


Figure 3. Front & back covers of the second volume of *Collected Works of Chia Yung Hsieh*

3.3. Volume 3

The third volume includes 55 papers and reports on coalfield geology and coal petrology completed by Professor Hsieh in the 40 years from 1916 to 1956, as well as 4 coalfield geology and coal petrology translations from the scientific translation series *Coal Genesis Types and Coal Petrology Research* published by Science Press in 1955 (Figure 4).

Among them are *Coal*, the earliest monograph on coal geology and coal mining in modern China; *A microscopical study of some coals from Szechuan, S.W. China* which pioneered coal petrology in China; *Some New Methods in Coal Petrography*, *Microscopic Study of Domestic Coal and Fuel Research and China's Fuel Problems*. *Coal Field & Coal Mining Industry in China, a General Survey* which has an important position in the history of China's coalfield geology and coal industry, *The Discovery of the New Coalfield in Huainan* which records a glorious page in the history of China's geology and mining, and important geological works such as *Coal Geology Research*, *Some Geological Problems in Exploring China's Coalfields*, *China's Coalfields*, *Coal Genesis Types and Their Significance*, and *China's Coalfield Types and Coal Quality Changes (Outline)* .

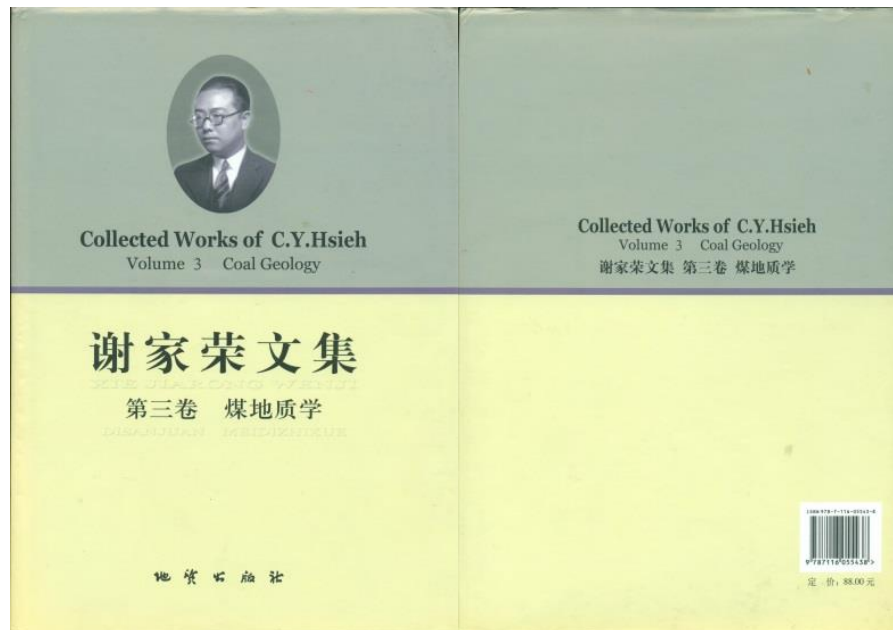


Figure 4. Front & back covers of the third volume of *Collected Works of Chia Yung Hsieh*

3.4. Volume 4

The fourth volume includes one monograph on petroleum geology completed in 1929 and 49 papers (including 7 papers in the *Petroleum Geology Collection* in 1957) by Professor Hsieh between 1916 and 1966, 2 translations, and 4 translations from the scientific translation series *Academician Gubkin and Petroleum Geology* published by Science Press in 1954, as well as the preface written for the translation series (Figure 5).

Among them are the first petroleum geology report written by a Chinese, *Gansu Yumen Petroleum Report*; China's first petroleum geology monograph *Petroleum* that systematically discusses terrestrial oil generation; *China's Petroleum Reserves (Abstract)* which was the first to calculate China's oil reserves; *On Oil Exploration in the Region South of the Yangtze River* which was the first to clearly point out that China's oil is not limited to the northwest; *Expanding the Scope of Oil Exploration*-which was firstly to expound China's correct oil exploration strategy; *Opinions on Northeast Oil Shale and Petroleum Minerals* which was firstly to point out that "the most important minerals that have not been discovered in the Northeast are oil,....."; *China's Oil-Producing Areas and Potential Oil-Bearing Areas* which provided an important basis for the selection of strategic areas for China's oil reconnaissance and exploration in the 1950s; *Reports at the Third Oil Reconnaissance Work Conference*, which comprehensively guided China's three-year oil reconnaissance; and *China's Oil-Producing Areas and Potential Oil-Bearing Areas and Opinions on Future Exploration Work*, which made ideological and theoretical preparations for the eastward shift of the focus of oil exploration strategy.

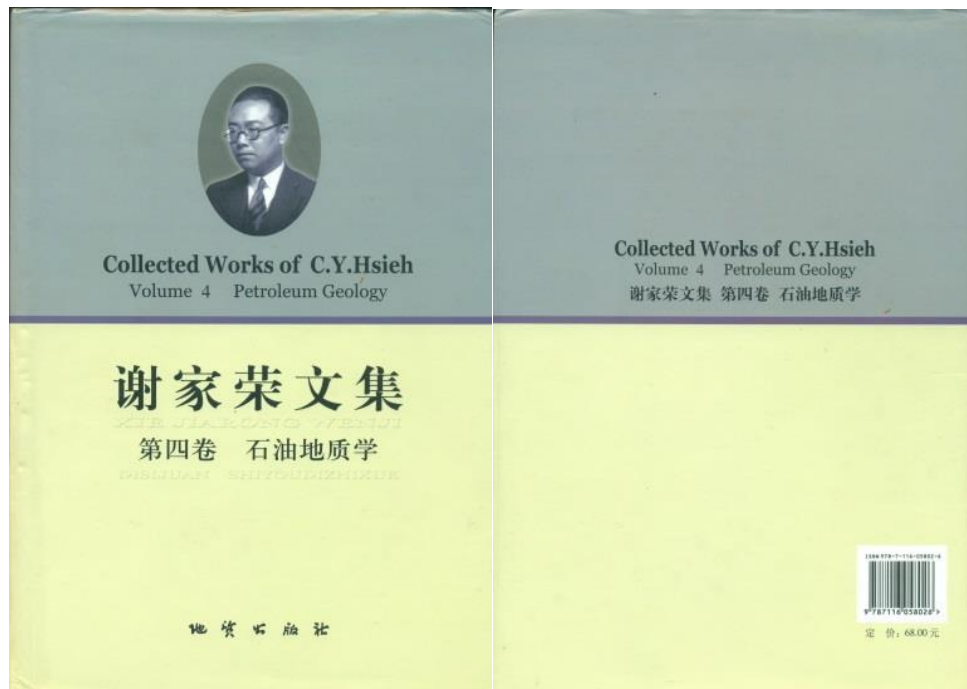


Figure 5. Front & back covers of the fourth volume of *Collected Works of Chia Yung Hsieh*

3.5. Volume 5

The fifth volume contains 17 papers and 3 monographs written by Professor Hsieh between 1915 and 1936, and 9 book and newspaper reviews on ore deposits published in *Geological Review* between 1936 and 1948 (Figure 6).

Among these works, there are *An Outline of Mineral Deposits* which pioneered the study of Chinese mineral deposits and *On the Late Mesozoic-Tertiary Orogenesis and Vulcanism, and Their Relation to the Formation of Metallic Deposits in China* which has an important position in the history of the development of Chinese mineral deposits. The three monographs such as *The Iron Ores and Iron Industry of China* (compilation and review), *The Iron Deposits of Southern Anhui* and *Geology of the Iron Deposits in the Lower Yangtze Region* embody a lot of Professor Hsieh's efforts and are important documents in China's mineral deposits. The book *Geology of the Iron Deposits in the Lower Yangtze Region* has been an important reference for prospecting in the middle and lower reaches of the Yangtze River for many years.

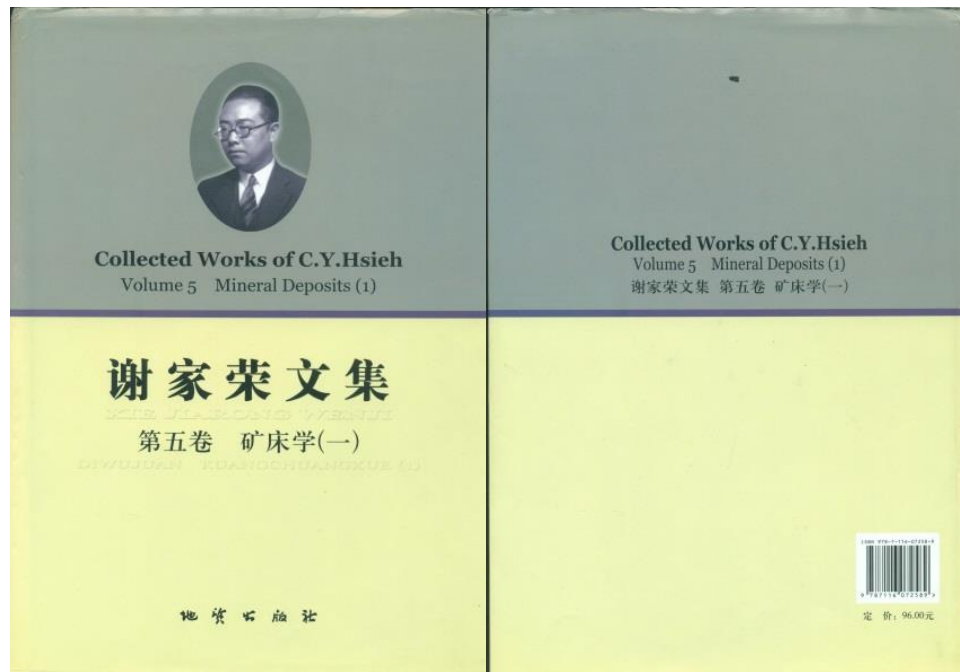


Figure 6. Front & back covers of the fifth volume of *Collected Works of Chia Yung Hsieh*

3.6. Volume 6

Volume 6 contains 44 papers and two monographs, namely, *The Lead-Zinc Deposits of Central Hunan* and *Mineral Deposits in China* written by Professor Hsieh between 1937 and 1966 (Figure 7).

Among the 44 papers, there are the famous *Report on Iron Ores in Kwanyinshan, Shuicheng and in Tiehkuangshan, Heichang, Kueichou, Tin placer deposits in Fuhochungkiang area, northeastern Kuangsi and southern Hunan, and with a note on the distribution of tin belts in China, Note on the ore deposits in the Yunnan-Kueichou-Sikang area with special reference to their distribution & geological age, A Brief Introduction to Uranium Ore, Bauxite in Zhangpu County, Fujian, Note on the phosphate deposits in China, Note on the lead, zinc and silver deposits in China, The Significance of Volcanoes and Volcanic Sedimentation in Several Mineral Deposits in China, and the first publication of Mineralization Problems in Yanshan Area, Several Problems in the Chromite Ore Area of Suolun Mountain, Geology and Mineral Deposits in the Bayan Obo Area, Several Problems on the Study of Tungsten-Tin Deposits in China, Granitization and Mineralization*, etc. The new edition of *Mineral Deposits in China* adds Chapter 11 (Abstract) according to the original intention of the author.

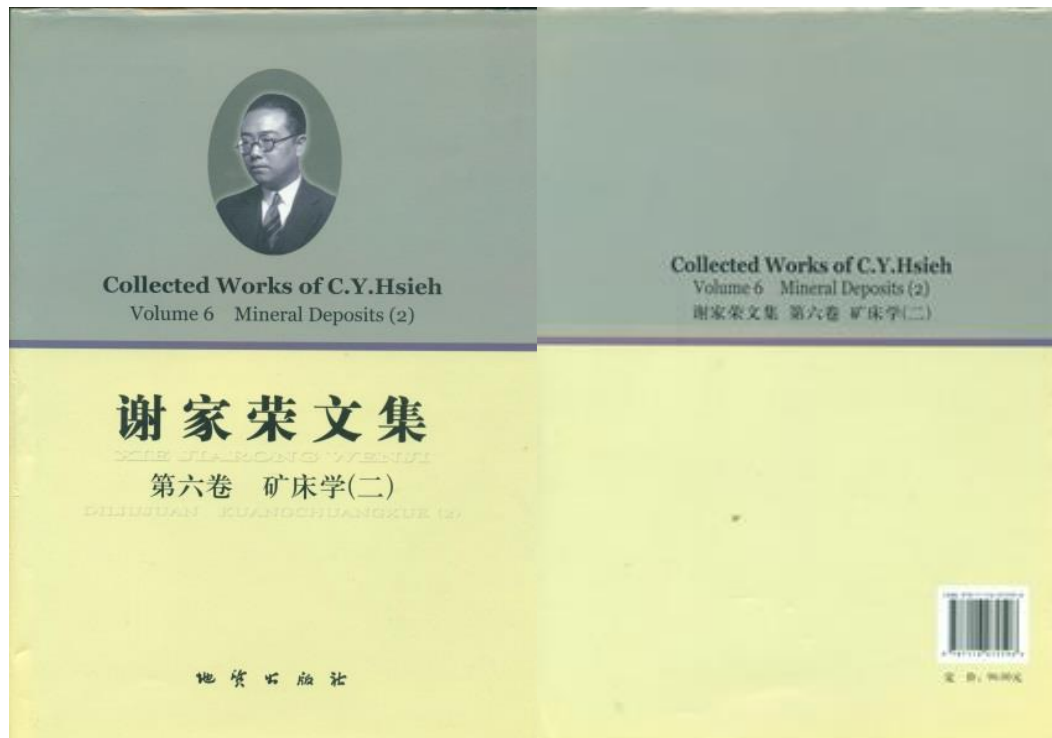


Figure 7. Front & back covers of the sixth volume of *Collected Works of Chia Yung Hsieh*

3.7. Volume 7

Volume 7 contains 37 papers and 6 monographs written by Professor Hsieh between 1921 and 1945 (Figure 8).

Among the 37 papers, there are, *Notes on the National Geological Survey of America* (the author's report on the inspection of Geological Survey of America (GSA) on the eve of his return from the United States), *Geological Research in the United States*, the Chinese translation of the paper submitted to the 14th International Geological Congress, *Pyrite and Sulfur Refining in China*; *Editorial of Geological Review*, *Progress in Economic Geology in China in Recent Years*, *Brief Reports on Tin Placers in Fuhochungkiang, Kuangsi*, *An Outline of Mineral Resources of Yunnan*, *A General Discussion on Bauxite in China* and *Results of Our Research on Bauxite in Kueichou and Yunnan*.

The six monographs are *An Overview of Geology and Mineral Resources of Hubei* co-authored with C. C. Liu in 1924, *General Statement on the Mining Industry (1918-1925)* in 1926, *Geology and Mineral Resources of S.W. Hupeh* co-authored with C. C. Liu in 1927, *Foreign Investment in Mining of China* co-authored with Minzhang Zhu in 1932, *Geology and Mineral Resources of Anxi, Yongchun and Yongtai in Fujian* co-authored with Y. C. Cheng in 1936, and *Geology and Mineral Resources between Weining and Kunming along the Xukun Railway* in 1941.

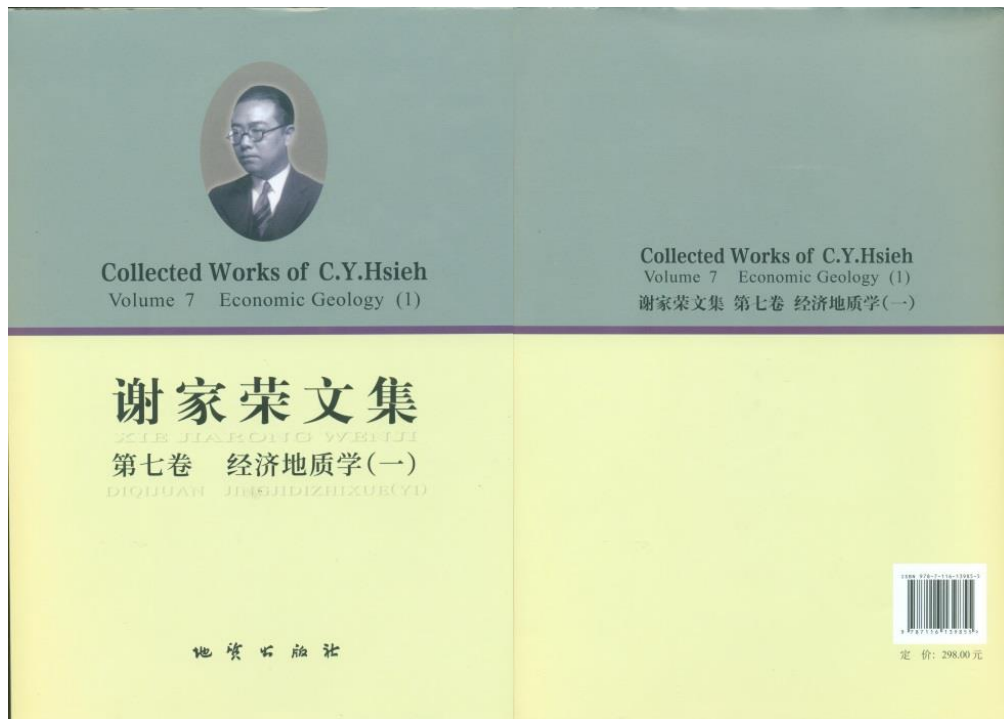


Figure 8. Front & back covers of the seventh volume of *Collected Works of Chia Yung Hsieh*

3.8. Volume 8

Volume 8 contains 132 papers and 3 monographs written by Professor Hsieh between 1945 and 1966 (Figure 9).

Among the 132 papers, there are *The Results of Our Research on Bauxite in Kueichou and Yunnan*, the famous *Palaeogeography as A Guide to Mineral Exploration*, *Annual Work Summary of the 37th Year of the Republic of China*, *Overview of Geology and Mineral Resources in Northeast China and Some Opinions*, *Some Opinions on the Future Range of Reconnaissance Based on Some Laws of Chinese Mineral Deposits*, *Distribution Laws and Prediction of Chinese Mineral Resources*, *Mineralization Theory and Prospecting*, *Let the Study of Granite and Granitization Serve the Purpose of Regional Geological Survey and Prospecting*, etc.; and Hsieh's last paper in his life is *Geotectonics and Prospecting* which has never been published before. The three monographs are *Basic Knowledge of Prospecting and the Discovery of Underground Resources in My Country* in 1953, *Reconnaissance Notice* (co-authored) in 1954, and *Preliminary Study on the Distribution Laws of Chinese Mineral Resources and Some Opinions on the Future Range of Reconnaissance* in 1958 which has never been published.

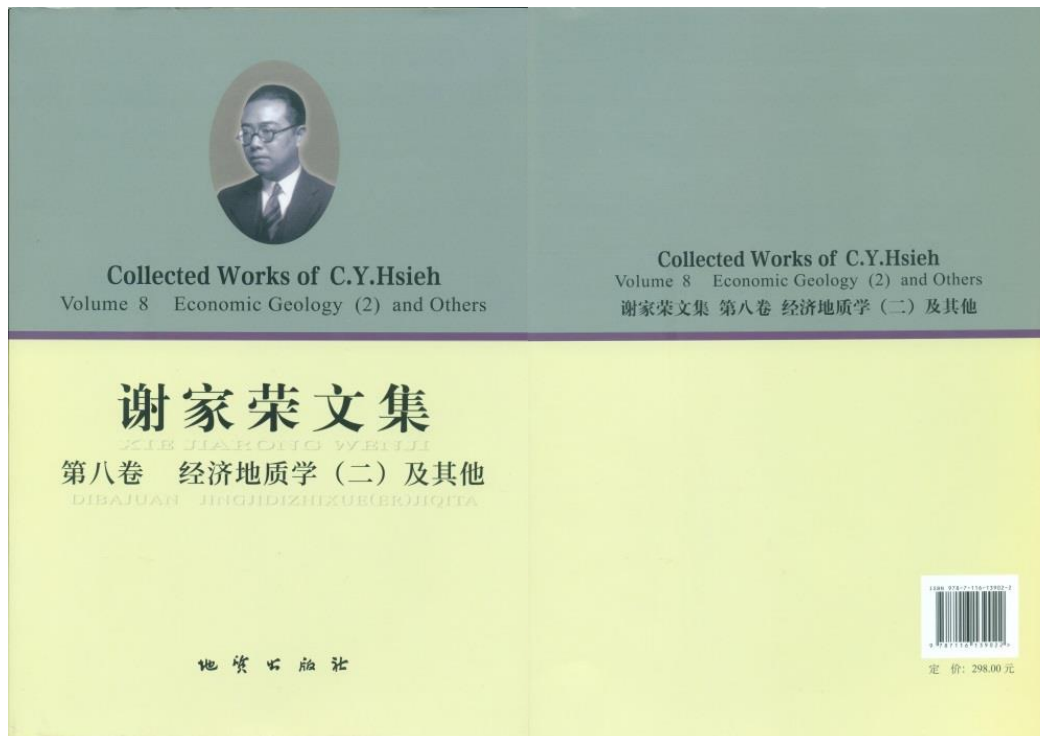


Figure 9. Front & back covers of the eighth volume of *Collected Works of Chia Yung Hsieh*

4. The difficult and long publishing process

In the spring of 2005, after learning that the three-volume *Selected Works of Y. C. Cheng* would be fully funded by the Ministry of Land and Resources and published by the Geological Publishing House, Prof. Zhang immediately suggested to Academician Xuejing Xie (Hereafter referred to as Prof. Xie) that 30 academicians of the Chinese Academy of Sciences and the Chinese Academy of Engineering should be recruited to jointly propose to the Ministry of Land and Resources to prepare for a celebration of the 110th anniversary of Chia Yung Hsieh's birth and apply for 500,000 CNY in publishing funds from the Ministry to publish the *Collected Works of Chia Yung Hsieh*. Prof. Xie immediately agreed and commissioned Prof. Zhang to draft a letter of advice to the Minister of Land and Resources.

After obtaining the consent of most of the 30 academicians (not yet completed), considering the special political environment in China, Prof. Xie finally decided to write a letter to Xianlai Meng, director of the China Geological Survey at that time, and to the Minister of Land and Resources on April 30 of that year, clearly proposing "suggestions on holding commemorative activities for the 110th anniversary of the birth of the famous geologist Professor Hsieh and publishing the *Collected Works of Chia Yung Hsieh*. It is suggested that "the funds needed to organize the commemorative activities shall be budgeted by the commemorative activities preparation group according to the activities and reported to the Ministry of Land and Resources, and the Ministry of Land and Resources shall allocate the funds". At the same time, it is suggested that "the Ministry of Land and Resources" allocate 500,000 CNY for the editing and publishing of the *Collected Works of Chia Yung Hsieh*, and the funds shall be used for the specific purpose", and "the funds allocated shall be controlled by the editorial committee, and no individual shall use them for other purposes for any reason." Later, the Chinese Academy of

Geological Sciences also made similar suggestions to the China Geological Survey. In May of the same year, the editorial committee of the *Collected Works of Chia Yung Hsieh* was established, and the editing work started immediately.

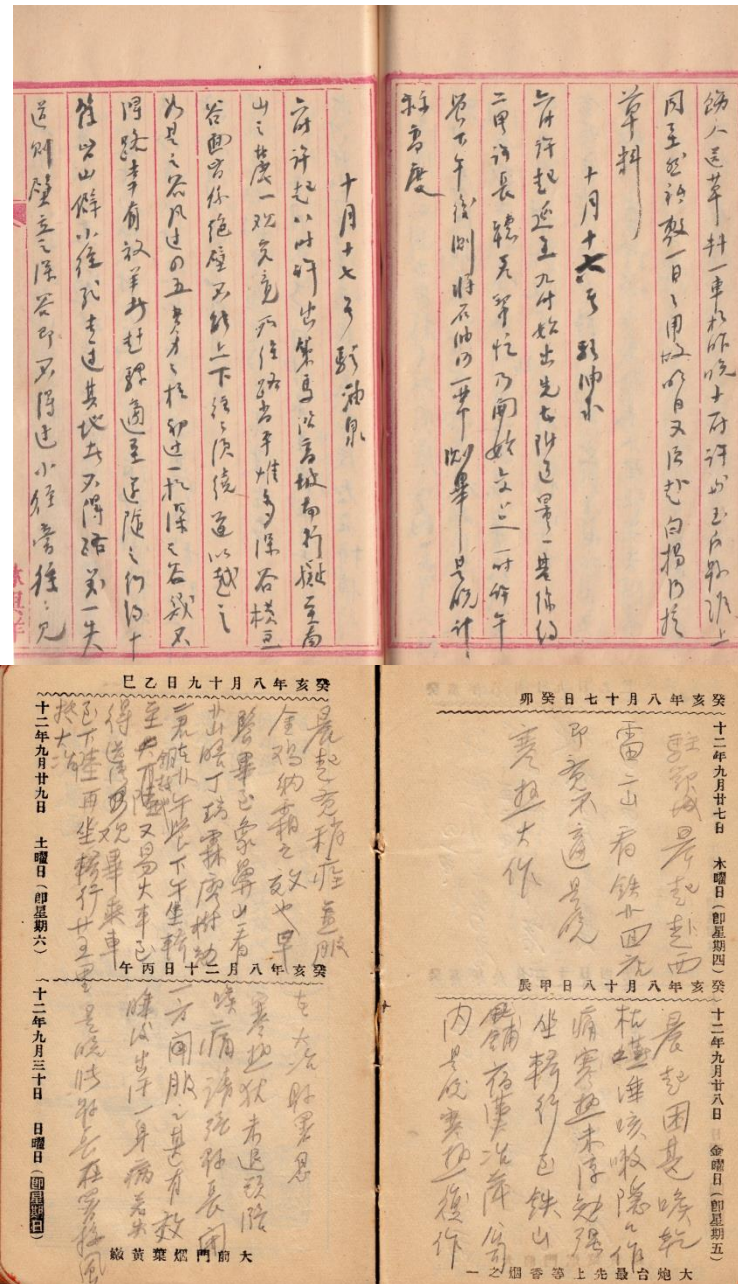


Figure 10. Photocopy of Mr. Hsieh's partial journal during field geological survey During the inspection of the Yumen oilfield in Gansu on October 17, 1921 (upper); on the way to investigate the geology in Hubei on September 27, 1923 (lower)

On April 19, 2006, the China Geological Survey made the following decisions on the commemoration of the 110th anniversary of Chia Yung Hsieh's birth:

- The commemoration will be organized by the Geological Society of China and the Chinese

Academy of Geological Sciences;

- The required funds will be self-raised in principle, and if there are difficulties, they can apply for individual project funds;
- The commemoration will include holding symposium and publishing a collection of papers.

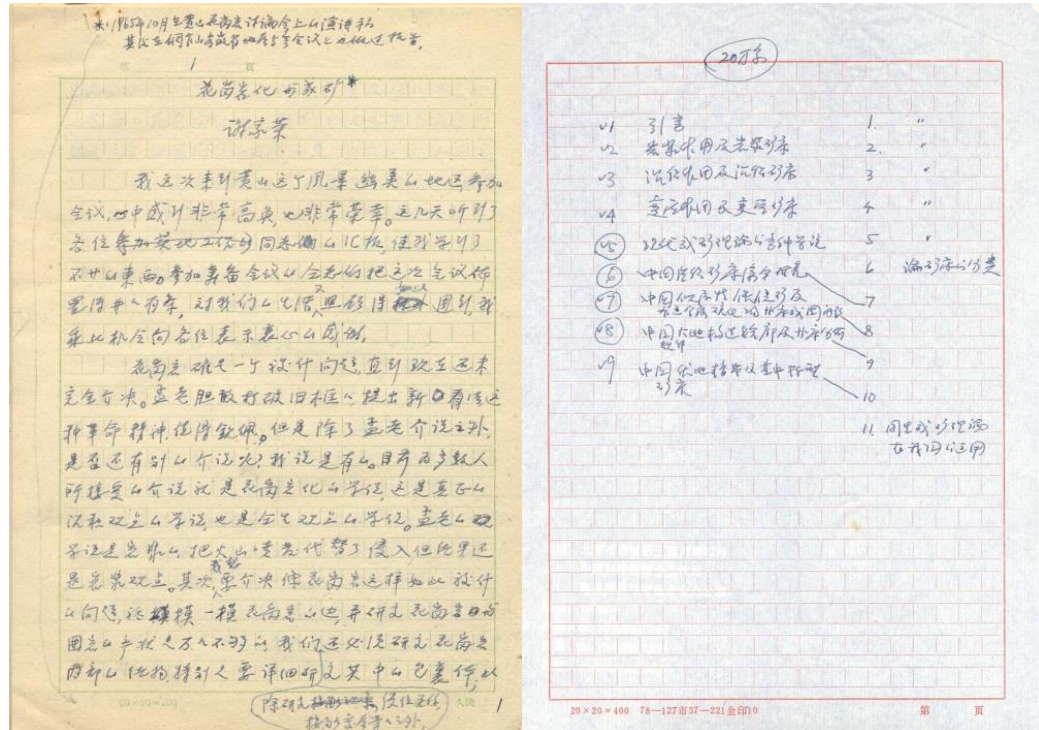


Figure 11. Photocopy of Mr. Chia Yung Hsieh's manuscripts

Left: Manuscript of the report *Granitization and Mineralization* at the Huangshan Granite Symposium in October 1965; Right: The catalogue manuscript of *Mineral Deposits in China (General)* personally written by Hsieh in 1966

The zero funding from the relevant departments brought endless troubles to the publication of *Collected Works of Chia Yung Hsieh*. For this reason, Prof. Xie allocated part of the funds from his own project and went through great pains to obtain partial funding from the Beijing Jianlong International Investment Co., Ltd. These self-raised funds enabled the first to fourth volumes of *Collected Works of Chia Yung Hsieh* to be published successively from January 2007 to August 2008.

On August 20, 2009, Prof. Xie wrote to Min Wang, then Vice Minister of the Ministry of Land and Resources and Director of the China Geological Survey, trying to raise funds to publish the collection. But there was no positive result. On May 31, 2010, Prof. Zhang wrote to the Institute of Geophysical and Geochemical Exploration on behalf of the Editorial Committee of *Collected Works of Chia Yung Hsieh*, hoping that the institute could solve the publishing funds, but there was no result.

After that, Prof. Xie and his students tried every means to raise some funds which were able to publish the fifth and sixth volumes of *Collected Works of Chia Yung Hsieh* in July 2011. But until Prof. Xie passed away in February 2017, more than five years later, the seventh and eighth volumes were still not published, and the main reason was lack of funds. After that, a student of Prof. Xie who worked at Tsinghua University planned to sponsor the funds, but in the end there



was no result. After that, Prof. Zhang communicated and applied with relevant parties for the publication of the collection many times, but there was no result.

After the hope of completing the publication of the *Collected Works of Chia Yung Hsieh* through official funding was completely shattered, in August 2020, Dr. Yuanhong Xie, the eldest grandson of Hsieh and the eldest son of Prof. Xie, called Prof. Zhang from Berlin, Germany and said, "Not only because Hsieh is my grandfather, but also because of the importance of this person who made so many contributions to Chinese geology throughout his life and his works", he and his three sisters (Yuanru Xie, Yuanquan Xie and Yuanjie Xie) decided to raise 200,000 CNY for the publication of the last two volumes of the Collected Works. This finally made it possible to publish the seventh and eighth volumes more than 13 years after the publication of the fifth and sixth volumes.

Thinking of the tortuous experience of publishing the eight-volume *Collected Works of Chia Yung Hsieh* for more than 16 years, Prof. Zhang still sighs. In fact, his feelings are more than that. When collecting and arranging Mr. Hsieh's old works, there were also many difficulties. Mr. Hsieh has been engaged in geological work for 50 years and left more than 400 articles (books). Mr. Hsieh's materials, especially many of his precious manuscripts, were lent out and lost in the following decade. The two wooden boxes of Mr. Hsieh's materials, which were originally stored in the reference room of the Chinese Academy of Geological Sciences, disappeared after being taken out by Prof. Xie, which became a "great loss and regret" in the heart of the executive editor Prof. Zhang. For this reason, Prof. Zhang said in the "Postscript to the Fourth Volume" that "if we can find something before the eight volumes of the collection are published, we will add it to the last volume." Unfortunately, despite their best efforts, the lost materials were not found.

Prof. Zhang, who was always thinking about this, worked hard to include Mr. Hsieh in the academic growth data collection project for senior scientists in 2013, and collected three important documents during the project. One of them was a report entitled *Several Geological Issues in Coalfield Exploration in China* by Hsieh at the National Conference of Geological Workers on January 22, 1953. During the group discussion of the report in the afternoon of the same day, Hsieh gave written answers to these questions, namely *Answers to the Questions Discussed in the Report on Several Geological Issues in Coalfield Exploration in China*. The other was a transcript of Mr. Hsieh's report on *Oil Exploration Issues in Jiuquan Basin* made by him at the Yumen Mining Bureau on June 2, 1955, which answered the question of where to find the second Laojun Temple oilfield. There is also a report found in the archives of the Chinese Academy of Geological Sciences, namely, a report entitled *Preliminary Opinions on the Ore-bearing Prospects of Dabaoshan and Its Surrounding Areas* made by Mr. Hsieh at the farewell meeting of all representatives of the Comprehensive Team of the Guangdong Dabaoshan Polymetallic Ore Survey and Exploration Method Research Team on November 6, 1960. After deleting Hsieh's signature, this report was submitted to the Party Group of the Ministry of Geology and the Party Committee of the Chinese Academy of Geological Sciences as Annex II of the *Report of the Dabaoshan Working Group of the Chinese Academy of Geological Sciences* on November 18, 1960. Because his name was so tampered with, his article was buried in the dust of history.

As there is no absolute certainty about the publication of the seventh and eighth volumes of *Collected Works of Chia Yung Hsieh*, Prof. Zhang included the full text of these three articles in the *A complete chronicle of Chia Yung Hsieh (C. Y. Hsieh)* that was published in December 2022. This can be regarded as a kind of compensation for the immeasurable merit. It is worth copying here the following statement from Prof. Zhang:

Finally, I need to make it clear to all readers that due to the huge workload of publishing the eight volumes of the collection, many people on the editorial committee are already over 60 or even 80 years old, and most of the other editors have their own busy business. The main editing work is undertaken by me. Due to my limited ability, mistakes are inevitable in the editing work. The most obvious is that some articles that obviously do not belong to the category of "economic geology" are included in these last two volumes. Due to various reasons they were not included in the first and second volumes and had to be put in these last two volumes. This is to make a statement and apologize to the readers.

101 years ago, Chia Yung Hsieh contacted P. L. Yuan to propose the establishment of the Geological Society of China. The 100th anniversary of the establishment of the Geological Society of China has just passed. It is a pity that the *Collected Works of Chia Yung Hsieh* could not be published before this. But it is a blessing in disguise that it can finally be published. On behalf of the editorial committee of the *Collected Works of Chia Yung Hsieh*, I would like to express my sincere gratitude and respect to all the geological colleagues who care about and support the publication of the collection! I am primarily responsible for all shortcomings and errors that occurred during the editing process of this book. I welcome readers' criticism and corrections.

Lisheng Zhang, Executive Editor, *Collected Works of Chia Yung Hsieh*
At the Hi-Tech West Zone, Chengdu, Sichuan, China
February 20, 2024

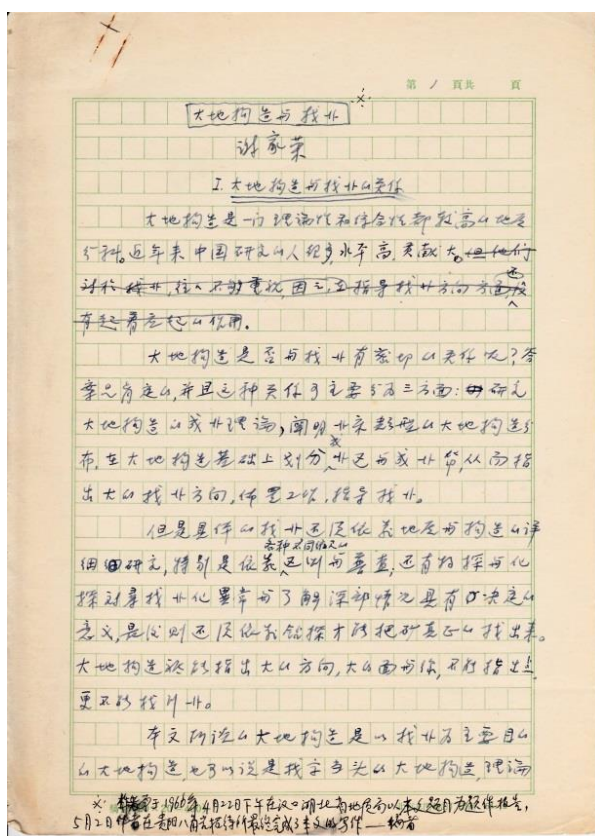


Figure 12. Photocopy of Mr. Chia Yung Hsieh's manuscript

On April 22, 1966, Hsieh gave a report on *Geotectonics and Ore Prospecting* at the Hubei Geological Bureau. This is the manuscript of his speech. Comparing Mr. Hsieh's manuscripts before liberation (Figure 10) and after liberation (Figures 11-12), we can find that his handwritings are very different. This has a lot to do with his state of mind at the times. In 1966, Hsieh and his wife committed suicide

5. Life is not easy, cherish every moment you have

From preparation in 2005 to the complete publication of the *Collected Works of Chia Yung Hsieh* in the end of 2024, it has gone through a long process. It is basically the time distance between two generations in the traditional Chinese sense. In terms of the average life span of human beings, most people have only a few 20 years in their entire lives.

In fact, the publication of this collection of works is not just a matter of time, but also the torment and anxiety of the editors. On the surface, the greatly extended publishing time is a matter of money, but in fact it is a problem of the unique political environment of this country. Otherwise, with the status of Prof. Xie, the eldest son of Mr. Hsieh, in the Chinese geological community, it would never take so long. And Prof. Xie himself did not see the full publication of this collection of works during his lifetime.

Those who understand the political ecology of this country understand the reason. No need to say more. In other words, if there was no Prof. Xie, the academican, this collection of works would never have been published.

In many cases, a country's political ecology not only determines the fate of the vast majority of people, but also determines the final judgment of a person after his death. No matter how great a person's contribution is during his lifetime, if it is not in tune with the political ecology of this land, it will only be buried or even disappear completely. This is the greatest sorrow in life.



Figure 13. Prof. Zhang (left), Executive Editor-in-Chief, *Collected Works of Chia Yung Hsieh*, and Academician Xuejing Xie in the office at the Baiwanzhuang, Beijing on March 22, 2002

6. Acknowledgements

All of the information and pictures in this article are generously provided by Professor Zhang, the executive editor-in-chief of the *Collected Works of Chia Yung Hsieh*.

Objectively speaking, without Prof. Zhang's hard work, there would be no *A complete chronicle of Chia Yung Hsieh (C. Y. Hsieh)* and no eight volumes of *Collected Works of Chia Yung Hsieh*. Or it should be said that without Prof. Zhang, our readers would not see such a detailed set of publications. Perhaps you may have only seen the first few volumes, not the relatively complete version now.

Without sufficient determination and patience, without the great determination and unparalleled spirit of traditional Chinese intellectuals to "establish a mind for heaven and earth, establish a destiny for the people, carry on the unique knowledge of the ancient sages, and bring peace to the world for all eternity", the above-mentioned books about Mr. Hsieh would hardly have been published.

In today's very secular and utilitarian era, almost no one is willing to spend their lives to collect the old materials of the old generation of scientists. Editing and compiling old books and articles in obscurity, especially scientific collections that cannot be sold at all, is obviously incompatible with the current Chinese social reality where everything is measured by money. Because editing these antiques depends entirely on the editor's heart, there is no benefit or income, and there will be no social status, but it will make some leaders unhappy.

Therefore, I would like to pay my highest respects to the editors of this set of books headed by Prof. Zhang. You are the disseminators and inheritors of the founders of Chinese science, and the best practitioners of Chinese traditional culture. These books are your immortal lifelong monuments and your great history.

At the same time, on behalf of the editors of this set of books (if possible), I would like to pay my highest respects to all those who have contributed to the publication of the collection!



Figure 14. Prof. Zhang in Shanbao Village, Jiuba Township, Guizhou in August 2024.

Data availability

The data that support the findings of this study is available from the author upon reasonable request.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



Use of AI tools declaration

The author declares that he has not used Artificial Intelligence (AI) tools in the creation of this article.

