



## Original Article

**Type and metallogenic series of the cobalt deposits in the East Kunlun, China**JZ Yin<sup>1,2</sup> **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

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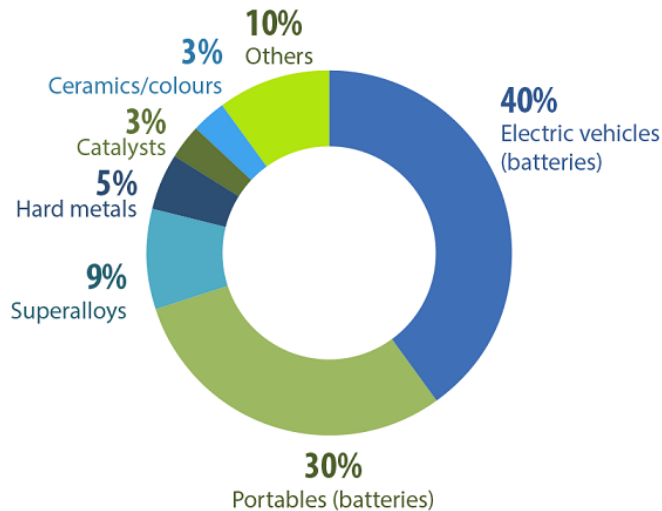
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## 1. Introduction

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)<sup>1</sup>, so I will not go into details here.



**Figure 1.** Global uses of cobalt in 2022<sup>1</sup>

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.

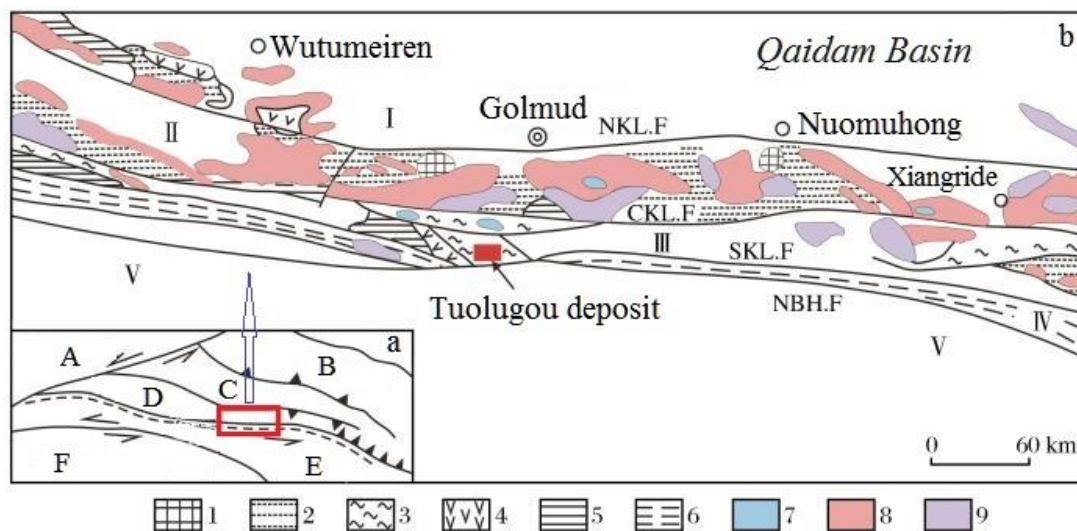
Based on the Chinese research results on cobalt resources published by geologists from mainland China in various domestic journals, this paper proposes the concept of the cobalt mineralization province in East Kunlun, China. Then, by summarizing the geological background of the main cobalt deposits in 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 China<sup>2-5</sup>.

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.<sup>2</sup>)

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-trending<sup>6-7</sup>, 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 orogeny<sup>8-10</sup>. 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)<sup>2</sup>, 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 direction<sup>11</sup>. 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 deposits<sup>12</sup>.

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

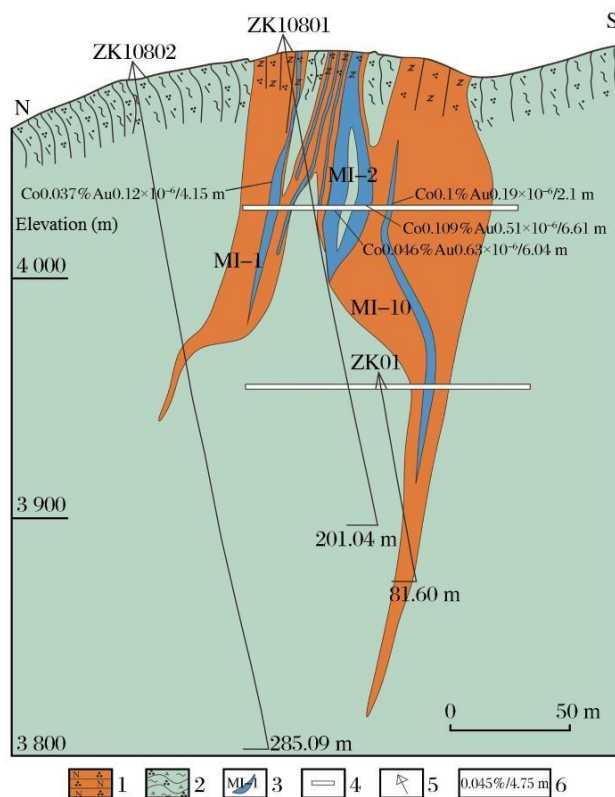
#### 3.1 Tuolugou Co-Au deposit, Qinghai Province

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  $0.45 \times 10^{-6} \sim 5.19 \times 10^{-6}$ <sup>13-15</sup>。

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 Ma<sup>16</sup>, 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.<sup>5,17</sup>. 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.<sup>18</sup>)

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 alteration<sup>14</sup>.

### 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 Basin<sup>19-20</sup>. 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.

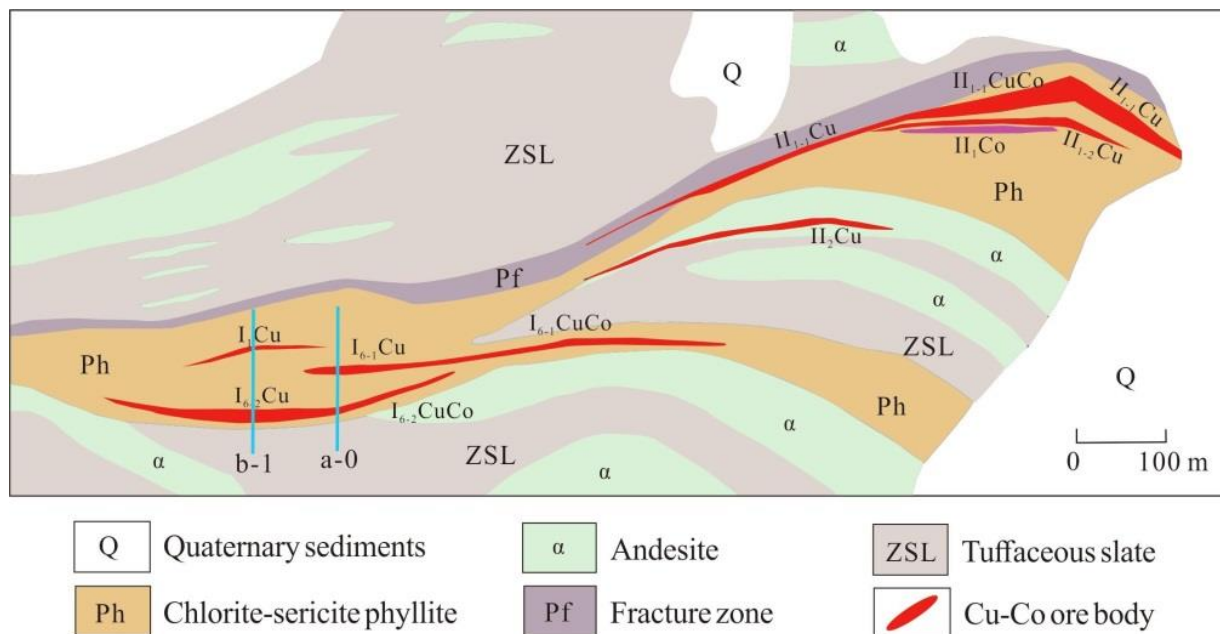
The Kendeke iron-cobalt-bismuth-gold polymetallic deposit is located in the Qimantag tectonic mineralization belt in the central volcanic basin of the Qaidam back-arc rift tectonic belt. The ore body is produced in the carbon mud calcium-iron siliceous rock formation of the Upper Ordovician hydrothermal 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 deposit<sup>20</sup>. 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%<sup>19-20</sup>.

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 area<sup>21-24</sup>. 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 ( $\alpha$ ) 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 acidic<sup>21-22</sup>.



**Figure 4.** The distribution of the ore body in the northern ore zone of the Mulonggou deposit<sup>24</sup>

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

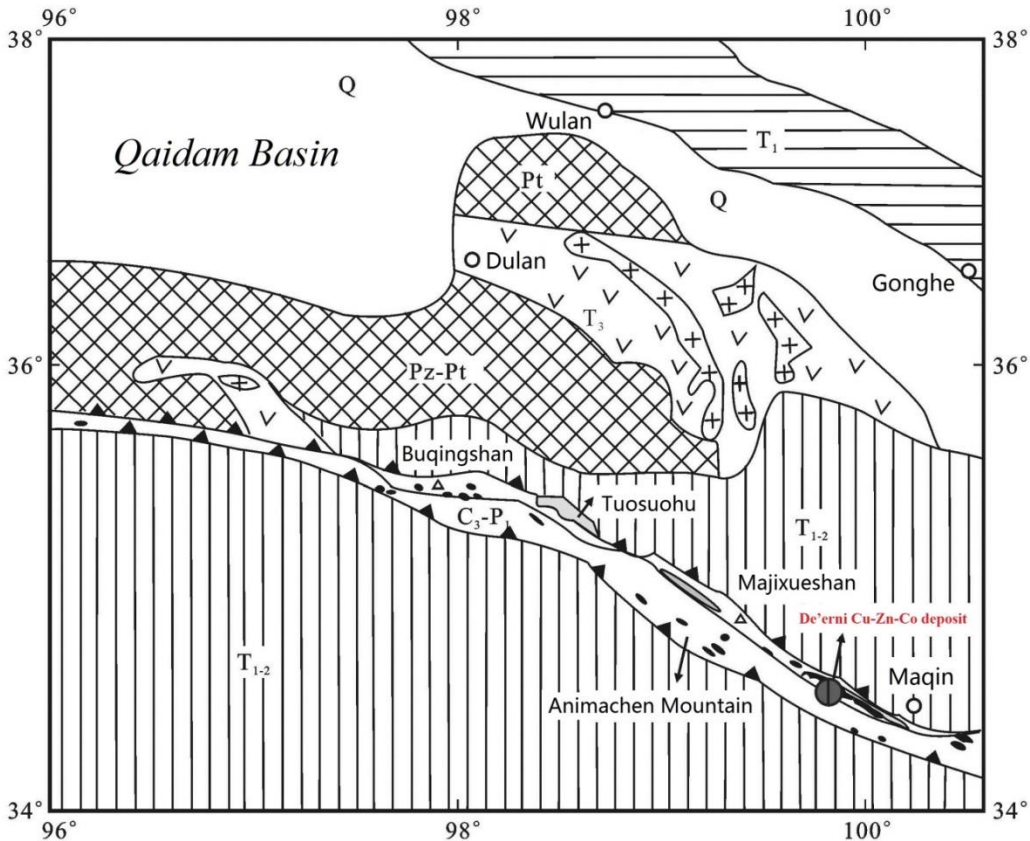
25 ore bodies have been identified in the area, 9 of which are distributed in the southern ore zone and the other 16 are distributed in the northern ore zone. The length of the ore body is between 106 and 335 m and the width is between 2.12 and 13.4 m. Some ore bodies are lens-shaped, some are vein-shaped, 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%<sup>25</sup>. 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)<sup>25-26</sup>. 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 pyrite<sup>26</sup>.



**Figure 5.** A brief geological map of the Animaqing ophiolite complex<sup>27</sup>

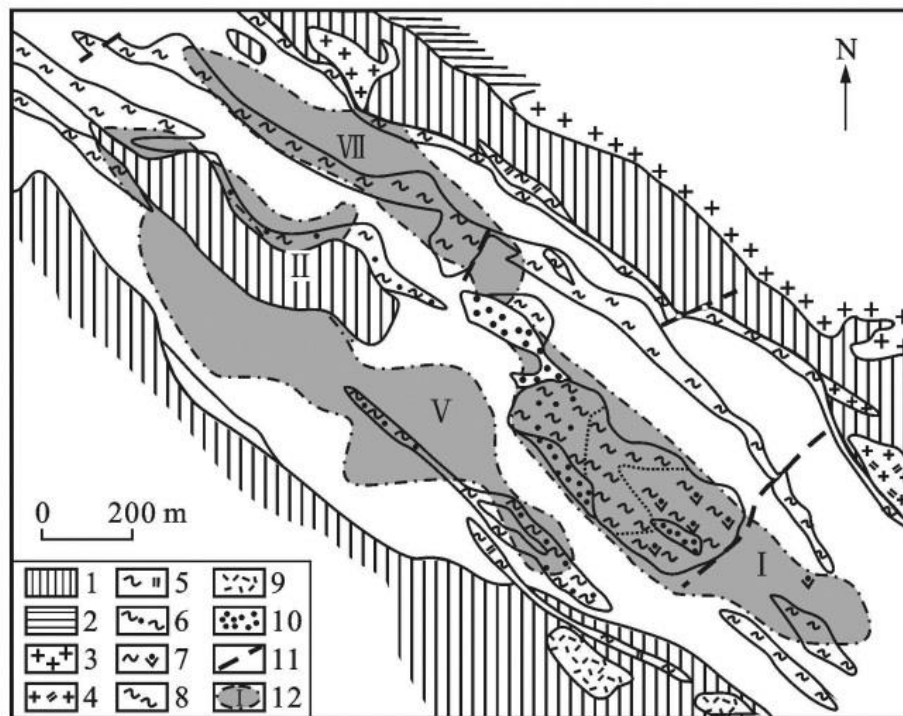
1. Quaternary slope deposits; 2. Upper Triassic sandstone and slate; 3. Middle and Lower Triassic sandstone and slate; 4. Lower Triassic complex formation; 5. Upper Carboniferous-Lower Permian bioclastic limestone, sandstone and slate, etc.; 6. Carboniferous limestone; 7. Paleozoic-Proterozoic amphibolite 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 ophiolite<sup>25-27</sup>, about 17 km long, 200~800m wide and 8~9 km<sup>2</sup> 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 lherzolite<sup>25-27</sup>. 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 pyrite<sup>25-28</sup>. 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  $56.7 \times 10^4$ ,  $2.85 \times 10^4$  and  $14.7 \times 10^4$  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 deposit<sup>28</sup>

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 zoning<sup>25</sup>: 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<sup>4,13-15,17-18,29</sup>. 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<sup>16,29</sup>. 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<sup>3-15,17,29-30</sup>. 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 origin<sup>15</sup>, there are also strata-controlled-reformation<sup>4</sup>, hydrothermal deposition-hydrothermal superposition transformation<sup>18</sup> and hydrothermal jet deposition-tectonic transformation, and other genetic view points<sup>12</sup>. 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 mineralization<sup>3</sup>. 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 deformation<sup>5</sup>.

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 period<sup>2</sup>. 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 rocks<sup>5</sup>. 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 zone<sup>19-20</sup>.

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 deposit<sup>21-24</sup>.

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 deposit<sup>21</sup>.

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 deposit<sup>22</sup>.

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 deposit<sup>24</sup>.

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  $295.5 \pm 7.2$  Ma<sup>26</sup>, 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 deposits<sup>26</sup>. The trace element content of its early pyrite, chalcopyrite and pyrrhotite is more similar to that of VMS-type deposits<sup>31</sup>.

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 Bi<sup>26</sup> 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 deposits<sup>32</sup>.

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 body<sup>33</sup>; the newly discovered "strawberry-shaped" pyrite with submarine jet deposition; the widespread

development of sedimentary structural features such as brecciated, lamellar, and banded structures<sup>34</sup>. The carbonate + quartz + barite + gypsum mineral assemblage was discovered<sup>35</sup>. The sulfur isotope composition  $\delta^{34}\text{S}$  is  $(-6.15 \sim 11.45) \times 10^{-3}$ , with an average of  $6.37 \times 10^{-3}$ . 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 deposit<sup>36</sup>. 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 carbonate<sup>37</sup>.

### 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%)<sup>23-25</sup>. 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.

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### 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.

