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ARTICLE

Origin of the Dashuigou Independent Tellurium Deposit at the Southeastern Qinghai-Tibet Plateau: Based on the Abundances of Trace Elements in the Country Rocks

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ABSTRACT

Through a detailed study of the abundances and spatial-temporal distribution patterns of Te, Bi, As, Se, Cu, Pb, Zn, Au, and Ag in the rock types of different geological epochs in the Dashuigou independent tellurium deposit, and in combination with other research findings of previous researchers in this area, the authors conclude as follows: Abundances of the main ore-forming elements Te, Bi, As, Se, Au, and Ag are not high in the regional geological background, generally lower or close to their respective crustal Clark values, but almost all altered country rocks contain high levels of ore-forming elements. This indicates that the deposit's ore-forming elements do not come from the country rocks. This also indicates that the geological thermal events that cause alteration and mineralization originate from depths and may be related to mantle plumes. Considering the distribution pattern of these ore-forming elements in the ore bodies' hanging wall and footwall, the metallogenic mechanism may be as follows: Mineralization is not achieved through lateral secretion in the horizontal or near horizontal direction, but rather through the upward movement and emplacement of deep ore-forming elements driven by geological processes such as mantle plumes. In addition, the migration of deep ore-forming elements is not achieved through dispersed infiltration between overlying rock particles, but through non widespread concentrated penetrating channels. This type of channel is likely to be the expansion structures where faults from different directions intersect, or where linear faults intersect with circular structures.

Keywords: Origin of ore-forming elements; The Dashuigou independent tellurium deposit; Trace element abundance; The country rocks; The mantle plume

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1. Introduction

The Dashuigou tellurium deposit, the only independent tellurium deposit in the world thus far, has attracted geologists' extensive attention, since its discovery in 1992. Thus many different views on its origins have been proposed [1-7].

Yin and Yin et al. proposed that the deposit's tellurium and bismuth originated mainly from the mantle's degassing in the form of a mantle plume, and enriched through nano-effect [1,5,6,8,9].

This paper's authors attempt to further prove the deposit's origin from the perspective of the abundance of trace elements in the deposit's country rocks.

2. Regional geology

2.1 General

Geotectonically in the transitional belt between the Yangtze platform and Songpan-Ganzi folded belt in the Qinghai-Tibet Plateau (**Figures 1 and 2**), the Dashuigou tellurium deposit is in the region where the crust-mantle structures and properties are the result of tectogenesis through various geological times, and have the following geophysical characteristics [1,8,10]:

- The turning boundary of the Earth's crust's thickness and the gravity gradient zone controlling the earthquakes and a series of mineral deposits.
- The abnormal mantle available and the upper mantle below the region uplifting obviously.
- The region exhibiting high geothermal flow, low-velocity, high density, high resistance, high magnetism, and low resistivity.
- The region has properties of both geosyncline and platform and is a geo-tectonically active zone with very complicated igneous rock structures.

In short, the study area is a place where the upper mantle and crust react frequently and the geological tectonic activity is very intense. It has therefore become a very important south-north trending tectonomagmatic-mineral belt [1,8,10].

2.2 Strata

Many of the strata in the study area are regional low-grade metamorphic rocks of the Silurian, Devonian, Permian systems, and lower-middle Triassic series, with a large amount of Archaean high-grade metamorphic rocks of the Kangding Group emerging to the southeast of the deposit.

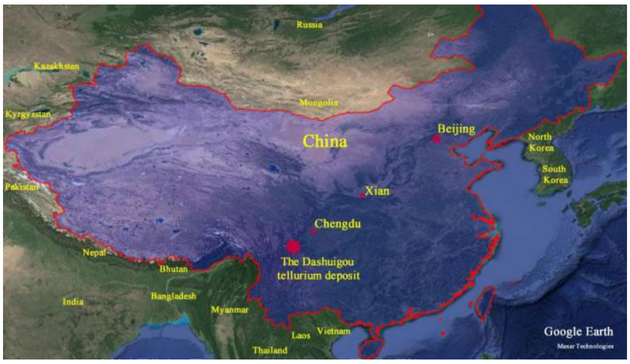

Figure 1. Location map of the deposit.

Source: Google Earth 7.1.8.3036 (32-bit): http://download.pchome.net/industry/geography/detail-20351.html, and 91 v17.5.8: www.91weitu.com; accessed January 25-27, 2020) [10].

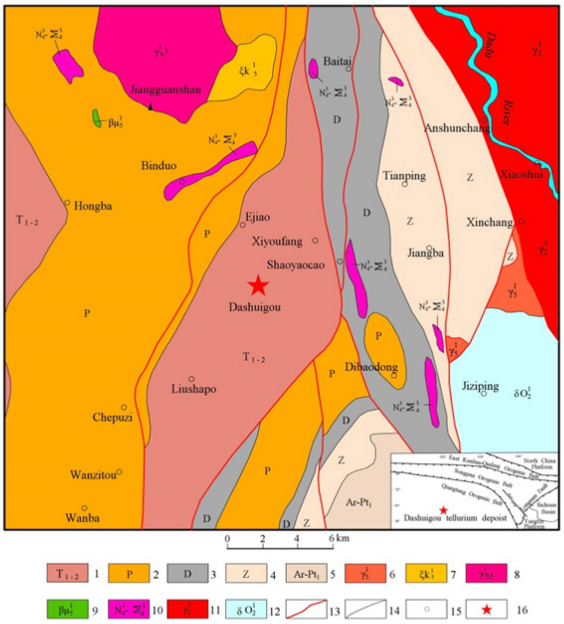

Figure 2. Regional geology.

1. The lower-middle Triassic metamorphic rocks; 2. The Permian metamorphic rocks; 3. The Devonian metamorphic rocks; 4. The Sinian metamorphic rocks; 5. Metamorphic complex of the Archean Kangding group; 6. Plutonic granite of the Indosinian orogeny; 7. Plutonic alkaline syenite of the Indosinian orogeny; 8. The Indosinian plutonic monzonitic granite; 9. The Indosinian hypabyssal sillite; 10. The late Hercynian basic-ultrabasic rocks; 11. The late Proterozoic plutonic granite; 12. The early Proterozoic-Archean plutonic quartz diorite; 13. The deep and large fault zone; 14. The geological boundary; 15. Village and/or town; 16. The tellurium deposit.

Source: [1,8].

The lithology and lithofacies of the deposit's hosts rock schist and phyllite, which have undergone multiple geological tectonic movements, change significantly.

The rocks in the study area have undergone various alterations such as dolomitization, muscovitization, tourmalinization, silicification, sericitization, and chloritization, and localized mineralization such as pyrrhotite, lead-zinc, copper, pyrite, tellurium, bismuth, gold, and silver [1,8,10].

2.3 Igneous rock

The igneous rocks including ultrabasic, basic, neutral, acid, and alkaline produced in different geological times are well-developed in the study area [1,8,11]. Large basic-ultrabasic, neutral, acid, and alkaline intrusive bodies exist beyond 10 km of the deposit include (**Figure 2**) the Archean-early Proterozoic Jiziping-Caluo quartz diorite and diorite, the late Proterozoic Xiaoshui granite, the late Paleozoic basic-ultrabasic intrusive rocks, and the Mesozoic neutral, acidic, and alkaline intrusive bodies including Jiangguanshan alkaline syenite, Jiangguanshan quartz diorite, and Xinchang granite.

In addition, a series of veins/dykes including quartz veins, carbonate veins, diabase dykes, granitoid aplite dykes, granite pegmatite dykes, and lamprophyre dikes etc. are widely developed in the study area.

The favorable geological conditions of strata, igneous rocks, and structures have created abundant mineral resources in the area, some of which are well known both domestically and internationally, including Ti, V, Cu, Pb, Zn, SM, REE, coal, asbestos, and the Panzhihua V-Ti-Fe deposit [1,8,11].

2.4 Structure

Well-developed annular and NW, NNE, NS, NWW, and NEE-trending linear structures are revealed by the remote sensing images in the study area (**Figures 3-6**) [1,8,11].

As we all know, the circular structure may be an external reflection of deep-buried igneous intrusive and/or geotectonic/geophysical anomalies, which helps to determine the formation mechanism of tellurium deposits in the study area.

Figure 3. Linear-circular structures based on remote sensing satellite images and geochemical anomalies in the study area (1:200,000).

As the largest known annular structure with a diameter of about 8 km in the area (**Figures 3 and 4**), the Xiyoufang composite ring's southern part reaches the Dashuigou deposit. Inside the Xiyoufang large ring, there exist two small annular structures with a diameter of about 2 km. Moreover, around the big ring, there are two other small rings accompanying it.

The annular structures and linear structures with different mechanical properties in different directions are cut with each other to form typical Ø-shaped structures favorable for mineralization (**Figures 3-6**). More than 20 tellurium mineralization showings including the Dashuigou tellurium deposit, and more than 10 Au-Bi composite geochemical anomalies, as well as several gold geochemical anomalies, are spatially related to these structures.

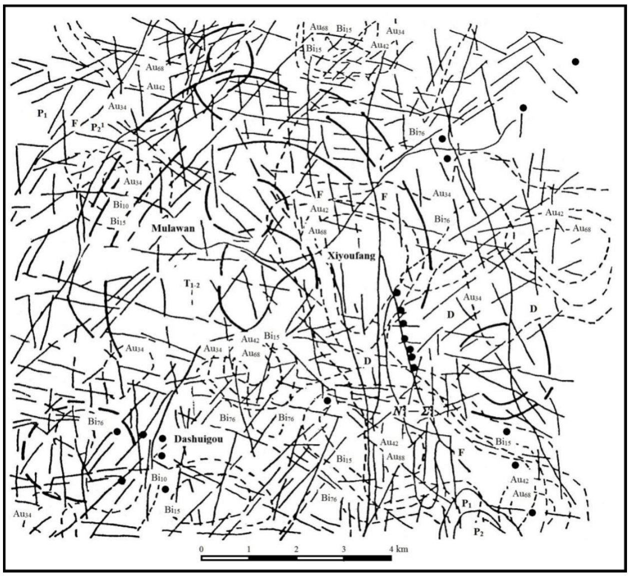

Figure 4. Linear-circular structures based on remote sensing satellite images and geochemical anomalies in the Xiyoufang area.

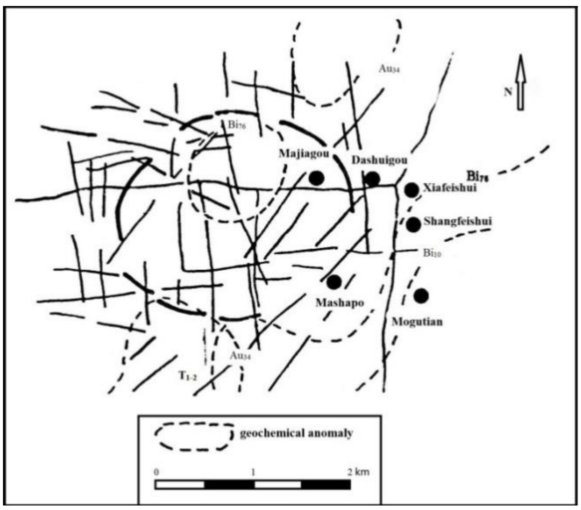

Figure 5. Linear-circular structures based on remote sensing satellite images and geochemical anomalies in the Dashuigou area.

As one of the Xiyoufang annular structure's sub-rings (**Figures 4 and 5**), the Dashuigou annular structure intersects with NE, EW, SN, and NW trending linear structures, forming a characteristic Ø-shaped structure controlling the unique deposit.

The perfectly circular Jinhuadong ring structure, Xiyoufang annular structure's other sub-ring, intersects with NWW, NNW, and SN-trending linear structures, forming another Ø-shaped structure controlling the Jinhuadong, Qifenyao, and Bafenyao tellurium showings, and several Au and Bi geochemical anomalies (**Figures 4 and 6**).

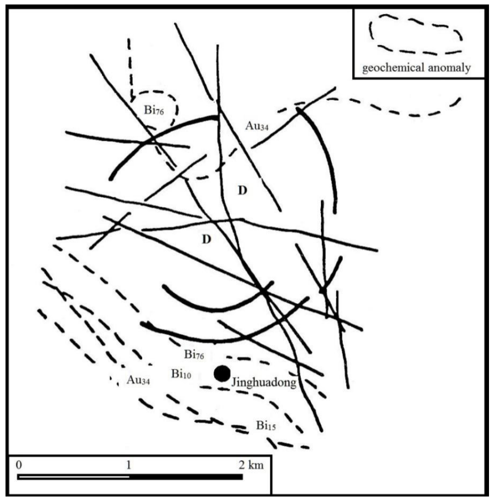

Figure 6. Linear-circular structures based on remote sensing satellite images and geochemical anomalies in the Jinhuadong area.

Baita, Tianwan, Tangjiapo, and Jiangguanshan are other annular structures in the area (**Figure 3**), all of which have a close spatial relationship with the Bi and Au geochemical anomalies.

Relatively tight, narrow, and long folds including the Dashuigou dome and Bindo anticline are mostly NNE or nearly SN-trending.

The over 10 km long and roughly NNE trending Dashuigou dome is entirely composed of lower-middle Triassic rocks (**Figure 5**). The dome's four sides are cut and bounded by NNW-trending, near-north-south, and NNE-trending faults respectively, forming a clearly flattened rhombic block.

3. Mine geology

The deposit's country and/or host rocks are the lower-middle Triassic marble, phyllite, and schist (**Figure 7**).

From top to bottom, Dashuigou tellurium deposit's country/host rocks include [1,8]: schist and phyllite on the top, the upper thick fine-grained marble, the middle schist and phyllite formation, the lower fine-medium-grained marble, and thick coarse-grained marble at the bottom.

The deposit's direct host rocks are the middle phyllite and schist including hornblende schist, garnet schist, tourmaline schist, and chlorite schist. Other minerals in the schist include quartz, plagioclase, potassium feldspar, muscovite, rutile, and magnetite (**Figure 7**).

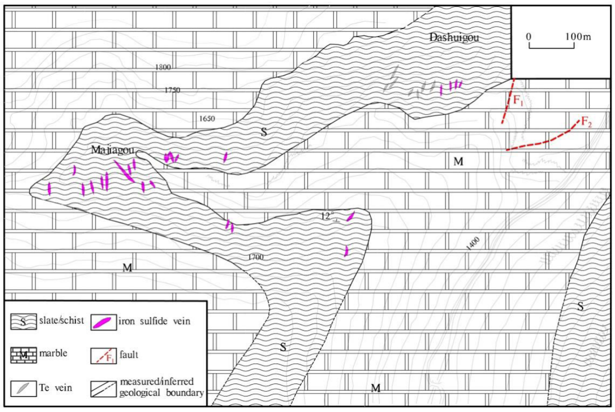

Figure 7. Mine geology.

Source: [1,8].

The NNE-trending Dashuigou dome is completely made up of the Triassic strata as mentioned above (**Figures 3-5**).

Most, if not all of the deposit's ore bodies in the shape of lenticular veins strike from 350 to 10 degrees, and dip at 55 to 70 degrees westward, with widths of which varying between 25 and 30 cm.

The alteration zones in the mining area are very narrow, generally ranging between several centimeters to one meter in width. The altered host rocks beside the massive ore bodies are narrower, at only several centimeters wide [1,6,8,10].

Approximately 40 minerals have been identified in the ore. Of all the ore types, the massive ore is the most important and disseminated ore is the secondary important. The tellurium grade in the ore varies between 0.01% and 34.58% [1,13-24].

Major ore textures and structures in the deposit include a replacement, remnant, reaction border, granular, massive, vein/veinlet, and stockwork veins [1,8,24].

Two paragenetic stages including five sub-stages in total have been recognized in the deposit; namely, the pyritic stage including carbonate sub-stage → pyrrhotite sub-stage → chalcopyrite sub-stage, and the tellurium stage including tetradymite sub-stage → tsumoite sub-stage (from early to late) [1,6,8,10,24,25].

4. Analytical methods

Multi Element ICP Analysis/LA-ICP-MS: A 0.5-gram sample is digested with 3 mL of a 3:1:2 (HCl: HNO_3: H_2O) acid, which contains beryllium that acts as an internal standard for 90 minutes in a water bath at 95 °C. The sample is then diluted to 10 mL with water and then analyzed on a Jarrell Ash ICP unit.

If the quality control standard is outside 2 standard deviations, or if the blank sample is greater than the limit, the entire set of samples is redone. The analytical results are collated by computer and printed along with accompanying quality control data; namely, repeats and standards.

5. Ore-forming element abundance in the country rocks

There are many geochemical anomalies in the study area, such as the Baita-Xiyoufang lead heavy sand anomaly to the north of the mining area, the scheelite heavy sand anomaly in the Hongba area to the northwest, the Guanyinshan-Nibapengzi nickel-chromium-cobalt-copper stream sediment anomaly to the southeast, the Landiao nickel-chromium-cobalt-copper-tin stream sediment anomaly to the southwest, the Ziershan Pass lead heavy sand anomaly to the south, and the geophysical as well as Bi and Au geochemical anomalies shown in **Figures 3-6**, etc.

The research area is located in the No.1 ore-forming prospect area in the 1:200,000 regional survey results, which is the prospect area of asbestos, iron, copper, lead, zinc, gold, and polymetallic minerals [11].

Overall, the geochemical anomaly zones within the area are closely related to certain lithology and have certain mineralization specific characteristics, such as copper, nickel, chromium, and cobalt mainly distributed in the development areas of basic-ultrabasic rocks. On the other hand, these anomalies are mostly located near and along fault zones, especially in areas with strong structural fragmentation, dense linear structures, and Ø-shaped structures [1,26,27].

Due to the extremely low crustal abundance of tellurium (**Table 1**) [28,30], coupled with previous human biases in understanding the mineralization ability of rare elements such as tellurium, as well as low testing accuracy, and many other factors, the study area, like the vast majority of regions both domestically and internationally, lacks regional geochemical background data on tellurium.

Table 1. The crustal abundance of tellurium published by different researchers.

Researcher	Clarke & Washington	Goldschmidt	A. Abeyc	Tong Li		
Year	1924	1937	1975	1976	1994	
Abundance	n × 10^{-8}	1.8 ×10^{-9}	1.0 × 10^{-9}	6.0 × 10^{-10}	2.0 × 10^{-8}	1.34 × 10^{-9}
Note	N/A	N/A	N/A	N/A	The Earth's crust in China	The Earth's crust world wide

6. Results and Discussion

In order to identify the abundance and distribution patterns of tellurium in the study area and provide sufficient basis for revealing the mineralization mechanism of the Dashuigou tellurium deposit, the authors of this article conducted quantitative chemical analysis of elements such as Te, Bi, Se, As, Au, Ag, Cu, Pb, and Zn in different rocks of different ages, including various metamorphic and igneous rocks, altered rocks, and highly developed carbonate veins in the study area. The results are shown in **Tables 2a and 2b**.

Among them, four elements, Te, Bi, Se, and As, were tested by atomic fluorescence spectrometry. Au, Ag, Cu, Pb, and Zn were tested by atomic absorption spectrometry. However, due to the limitation of the lower analytical limit, approximately 34% of the samples were unable to detect their exact abundance of Te. The detection limit of Te is 10^{-7}. As, Bi, Ag, Pb, Se, and Cu also have similar problems. This poses certain difficulties in accurately analyzing the abundance of relevant elements in different rocks and veins of different ages.

6.1 Te and Bi

According to **Tables 2a and 2b**, the distribution pattern of Te in the study area is summarized as follows:

The Te content in granite of different ages in the region is the lowest, less than 10^{-7}, close to the crustal abundance of tellurium (**Table 1**). This indicates a sense that the Dashuigou tellurium deposit's formation is not related to these granite intrusions. In addition, the three rock samples' δ^{30}SiNBS-28‰ values indicated that their protolith is an intermediate-basic volcanic rock [1,8,12].

The abundance of Te in the metamorphic rocks is significantly higher than that in granites mentioned above. However, there are significant differences in tellurium content in metamorphic rocks of different ages. The main performance is that the tellurium abundance is the highest in the Middle and Lower Triassic rocks, followed by the Devonian rocks, and the lowest in the Upper Permian rocks (**Figure 8**).

In metamorphic rocks of the same age, different rock types contain different amounts of tellurium. In general, schist and phyllite contain more tellurium than marble. The same is marble, because of the different particle sizes, the abundance of tellurium is also different. Coarse-grained marble contains low tellurium abundance and is close to the crustal abundance of tellurium (**Table 1**), while fine-grained marble contains a higher amount of tellurium. That is, the abundance of tellurium is inversely correlated with the grain size of marble.

Both are lower-middle Triassic rocks, and the horizons are basically the same, but the tellurium content of the rocks inside and outside the mining area is also different (**Figure 8**). This should be related to the different degrees of alteration and mineralization of the metamorphic rocks in the mining area during the thermal dome process. The periphery of the mining area has low tellurium content because it has not been subjected to heat or to a lesser extent.

Table 2a. Analytical results of trace element content in different rocks in the research area.

Rock	Age	Series #	Sample #	Name	Location	
	γ_5^1	1	SL-01	granite		Niubeishan, Xinchang
Igneous rock	Pt_3	2	SL-26	KF granite		Sanxing, Fengle
		3	SL-22	granite		By the Dadu River
		4	SL-07	fg marble		West of Miaoping
		5	SL-19	schist		Near the mine
		6	SL-12	schist	peripheral	Near Miaoping
		7	SL-17	fg marble		Near Tizigou
		8	SL-18	banded marble		Near Tizigou
		9	SL-16	mg marble		Near Tizigou
		10	SL-14	cg marble		East of Miaoping
		11	SL-15	cg marble		Near Tizigou
	T_{1-2}	12	SD-12-2	slate		Between ore zones # II-III
		13	SD-18	green schist		In the hanging wall of # III-3 ore body
		14	SD-32	slate		In the hanging wall of # I-4 ore body
Metamorphic rock		15	SD-43	green schist		In the hanging wall of # I-1 ore body
		16	SD-38	green schist	mine	In the footwall of # I-1 ore body
		17	SD-35	amphibole schist		In the hanging wall of # I-5 ore body
		18	SD-22	banded marble		In the foot wall of # III-3 ore body
		19	SD-69	cg marble		In the bottom of the Dashuigou ditch
		20	SL-03	slate		Near the river dam
		21	SL-04	green schist		Near the river dam
	P_2	22	SL-02	slate		North of Wanzitou
		23	SL-10	metamorphosed basalt	peripheral	Near Miaoping
	D	24	SL-21	marble		Northeast of Xiyoufang
		25	SL-20	slate		Northeast of Xiyoufang
		26	SD-02	sericite schist		In the adit of # II ore zone
		27	SD-37	sericite schist		In the hanging wall of # I-5 ore body
		28	SD-42	slate		In the hanging wall of # I-1 ore body
Strongly altered rock		29	SD-39	slate	mine	In the foot wall of # I-1 ore body
	177-80 Ma	30	SD-54-1	schist		In # 4 adit
		31	SD-68	green schist		at the portal of # 4 adit
		32	SD-49	banded marble		at the portal of # 4 adit
		33	SL-05	slate	peripheral	At Liushapo
Dolomite vein		34	SD-65-1	dolomite	mine	In # I-8 ore body
		35	SL-08	dolomite	peripheral	At Liushapo

Note: KF—potassium feldspar, fg—fine grained, mg—medium grained, cg—coarse grained.

Table 2b. Analytical results of trace element content in different rocks in the research area (× 10^{-6}).

Series #	Te	Bi	As	Se	Au	Ag	Cu	Pb	Zn	Average value
1	< 0.10	0.89	0.30	< 0.10	0.00	0.01	20.00	< 10	86.00	
2	< 0.10	0.18	0.80	< 0.10	0.00	0.01	4.00	63.00	42.00	Te < 0.10, Bi < 0.37, As 0.47, Se < 0.10, Au 0.02, Ag 0.01, Cu 10.67, Pb < 30.33, Zn 71.33
3	< 0.10	< 0.05	0.30	< 0.10	0.00	0.01	8.00	18.00	86.00	
4	0.90	1.34	1.10	< 0.10	0.00	< 0.01	1.00	< 10	98.00	
5	< 0.10	0.20	14.10	< 0.10	0.00	0.01	26.00	13.00	78.00	
6	< 0.10	< 0.05	0.10	< 0.10	0.02	0.06	122.00	12.00	122.00	
7	2.50	5.09	1.00	< 0.10	0.00	0.01	4.00	< 10	38.00	Te < 0.50, Bi < 0.88, As 2.78, Se < 0.10, Au 0.01, Ag < 0.02, Cu < 19.75, Pb < 15.75, Zn 61.38
8	< 0.10	< 0.05	5.60	< 0.10	0.01	0.01	2.00	< 10	41.00	
9	< 0.10	0.24	0.10	< 0.10	0.00	0.01	1.00	< 10	41.00	
10	< 0.10	< 0.05	0.10	< 0.10	0.00	0.06	1.00	51.00	21.00	
11	< 0.10	< 0.05	<0.10	< 0.10	0.00	0.01	1.00	< 10	52.00	
12	0.50	1.07	0.20	< 0.10	0.01	0.02	50.00	< 10	84.00	
13	4.50	10.60	<0.10	< 0.10	0.01	0.05	6.00	< 10	142.00	
14	4.70	9.17	0.20	< 0.10	0.00	0.01	20.00	< 10	99.00	
15	2.70	4.05	0.20	< 0.10	0.00	0.02	9.00	< 10	197.00	Te 8.35, Bi 12.27, As < 0.48, Se < 0.10, Au 0.004, Ag < 0.023, Cu < 21.75, Pb < 10.00, Zn 99.25
16	5.50	1.13	1.20	< 0.10	0.00	0.01	3.00	< 10	125.00	
17	37.10	56.10	0.20	< 0.10	0.01	0.06	81.00	< 10	78.00	
18	11.60	15.50	1.10	< 0.10	0.00	0.01	4.00	< 10	56.00	
19	0.20	0.52	0.60	< 0.10	0.00	0.01	1.00	< 10	13.00	
20	<0.1	0.10	4.10	< 0.10	0.01	0.02	12.00	12.00	86.00	
21	<0.1	0.19	0.40	< 0.10	0.00	0.06	102.00	< 10	154.00	Te <0.13, Bi 0.26, As 1.95, Se 0.10, Au 0.01, Ag 0.04, Cu 38.75, Pb 10.50, Zn 83.75
22	0.20	0.43	0.90	< 0.10	0.00	0.05	17.00	< 10	38.00	
23	<0.1	0.31	2.40	< 0.10	0.01	0.03	24.00	< 10	57.00	
24	<0.1	0.39	1.90	< 0.10	0.00	0.01	2.00	< 10	118.00	Te 0.60, Bi 0.47, As 0.63, Se 0.10, Au 0.01, Ag 0.06, Cu 2.00, Pb < 10.00, Zn 157.50
25	1.10	1.49	0.60	< 0.10	.0.012	0.10	2.00	< 10	197.00	
26	1.10	2.66	<0.1	< 0.10	0.00	0.01	34.00	< 10	92.00	
27	11.00	15.50	3.60	0.30	0.04	0.04	212.00	< 10	83.00	
28	4.60	5.98	0.20	0.40	0.00	0.01	130.00	< 10	145.00	
29	99.10	117.00	0.40	< 0.10	0.03	0.05	6.00	< 10	57.00	Te 44.15, Bi 52.77, As < 4.76, Se < 0.24, Au 0.02, Ag 0.06, Cu 68.50, Pb < 10.00, Zn 77.13
30	56.80	84.60	32.80	0.70	0.09	0.06	6.00	< 10	14.00	
31	0.40	1.05	0.60	< 0.10	0.01	0.11	121.00	< 10	164.00	
32	178.00	191.00	0.20	< 0.10	0.01	0.12	3.00	< 10	4.00	
33	2.20	4.38	0.20	< 0.10	0.01	0.09	36.00	< 10	58.00	
34	2.30	3.44	0.20	< 0.10	0.00	0.03	3.00	< 10	10.00	Te 31.90, Bi 20.39, As 0.15, Se < 0.10, Au 0.004, Ag 0.04, Cu 2.00, Pb < 10.00, Zn 7.50
35	61.5	78.1	< 0.10	< 0.10	0.0	0.0	1.0	< 10	5.0	

Note: If there is no definite value in the original numerical value, the average value is calculated according to its lower limit of analysis.

Laboratory: National Geological Chemical Analysis Center.

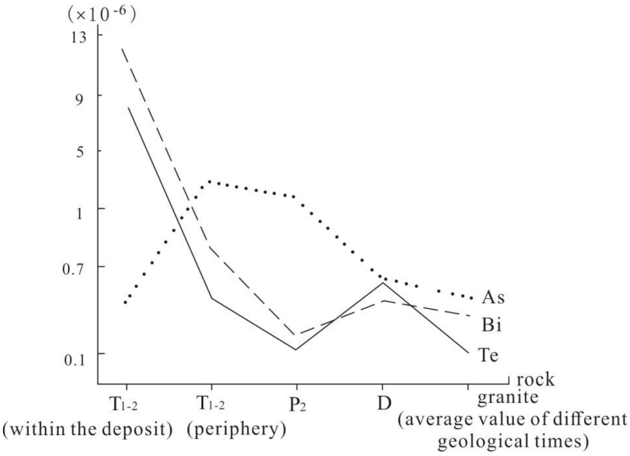

Figure 8. Te, Bi, and As abundances in metamorphic rocks and granites of different ages in the study area.

An important fact is that in the T1-2 formation outside the mining area, except for the two fine-grained marble samples near the Tizigou Pb-Zn showing (two samples with series numbers 4 and 7 in **Tables 2a and 2b** respectively), which may have undergone alteration, the crustal abundance of tellurium is slightly higher or close to that of tellurium in the Earth's crust. All other samples are lower or close to the crustal abundance of tellurium.

Anyway, the stronger the alteration that rocks undergo, the higher their tellurium content. This may to some extent indicate that the source of tellurium is not related to the host rock, but is closely related to alteration. In other words, the metamorphic rocks and granites of different ages in the study area are not the origin of Dashuigou independent tellurium deposit. The ore-forming materials, namely, Te, Bi, etc. come from mantle exhalation or mantle plumes that cause alterations.

Various geochemical evidence shows that the study area is an area where the deep crust and mantle materials are relatively developed. The δ^{30}SiNBS-28‰ of the deposit's schist samples indicate that the schist's protolith is basalt [1,8,11,12]. The REEs of the lower-middle Triassic phyllite, marble, and tourmaline quartz vein in the study area are similar to those of modern mid-ocean ridge tholeiite. The REE geochemistry indicated that the lower-middle Triassic phyllite evolved from basalt magma.

There is no doubt that the tellurium abundance of the rocks in the study area is positively correlated with the intensity of the alterations that these rocks undergo. Strongly altered rocks almost always have high tellurium content.

In both the periphery of the mine and the mining area itself, all dolomite in the study area has high tellurium content. This is consistent with the fact that dolomite is one of the important tellurium carriers in the mining area. This also indicates that dolomite veins are one of the important indicators for searching for potential tellurium deposits in the research area. On the other hand, it also reminds us that understanding the origin of dolomite may be one of the key factors in deciphering the mineralization mechanism of the Dashuigou tellurium deposit.

Another noteworthy fact is that the ore body host strata, namely the upper part of the lower-middle Triassic schist, especially the banded marble in the lower part, has a higher tellurium content (samples #4, 7, 18, and 32 in **Table 2b**), which is much higher than the underlying coarse grained marble belonging to the same carbonatite. This seems to mean that the ore-forming materials are not concentrated in the ore body host strata through bottom-up diffusion and infiltration, otherwise the underlying coarse-grained marble should be richer in tellurium than the overlying fine-grained banded marble, but the opposite is true. That is to say, the ore-forming material is likely to move up along a relatively concentrated and unified tubular channel, ultimately emplace to form the deposit. The ore-bearing fluid or likely telluride ore magma from the deep underground, driven by temperature and pressure, migrates upwards along this tubular fault channel, successively passing through coarse-grained marble and fine-grained banded marble layers, entering the schist layers and forming deposits in the expansion structures within them. The finer and denser schist layers than marble serve as a barrier layer.

It should be pointed out that this is only a theoretical assumption based on the abundance and spatial distribution of tellurium in the surrounding rocks of the study area, and other various geological and geophysical evidence is needed to support it.

The altered, unaltered, or weakly altered rocks in the footwall of the tellurium ore bodies all have higher tellurium content than similar rocks in the hanging wall (**Tables 2a and 2b**, **Figure 9**). This may mean that the ore-forming material is not accumulated through horizontal lateral secretion, but rather comes from the deep. In other words, the ore-forming elements do not originate from the host rock, but from the deep.

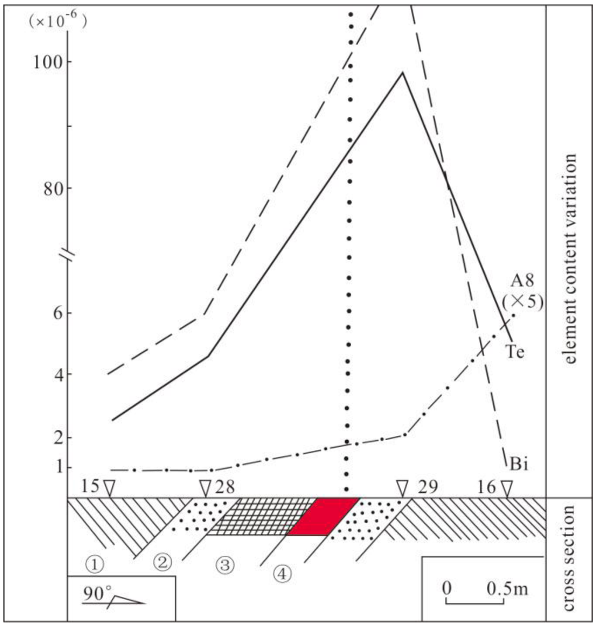

Figure 9. Cross section and trace element variation diagram of I-4 ore body in pit 1 of the mine.

① green schist, ② altered rock, ③ pyrrhotite vein, ④ tellurium ore body.

Bi and Te have almost identical patterns of change (**Tables 2a and 2b**, **Figures 8 and 9**). The abundance of Bi in Devonian rocks and granite is significantly higher than that in the Permian. In addition, the content of Bi in the Indosinian granite (0.89×10^{-6}) is also higher than that in the Chengjiang orogenic granite. In the Chengjiang granite, Bi tends to be enriched in alkaline granite rather than ordinary granite. But overall, the Bi content in these granites is still close to its abundance in the Earth's crust (0.17×10^{-6}, Taylor, 1964) and within the range of acidic igneous rocks. The abundance of Bi in acidic igneous rocks is 0.02×10^{-6}-0.90×10^{-6}, with an average of 0.18×10^{-6} [29].

Durin Balkovskaya (1976) found through a detailed study of the distribution of Bi in various ages of igneous rocks in the Kuraming Mountains of the former Soviet Union that the content of Bi significantly increased during the evolution process from early basic rocks to late acidic rocks, indicating that the enrichment of Bi in igneous rocks occurred in the late stages of each intrusive formation. After studying the distribution of Bi in the batholith of southern California and Iowa, Glenland (1976) reached a similar conclusion that Bi tends to accumulate in residual magma during magma differentiation [1,29].

The geochemical behavior of Bi mentioned above and its enrichment pattern in the study area indicates that the source and formation mechanism of the ore-forming material of the Dashuigou tellurium deposit is related to deep geological processes such as mantle plumes, but not directly related to the surrounding rocks.

6.2 As, Sn, Au, and Ag

The abundance of As in the Earth's crust is 1.7×10^{-6} (Vinogradov, 1962) or 1.8×10^{-6} (Taylor, 1964) [28-30]. In addition, the abundance of As in various rocks does not change much. In granite, neutral rocks, basalt, diabase, and gabbro, the abundance and distribution pattern of As are very consistent (Onich, H). Like Bi, As is mainly enriched in late rocks of magmatic differentiation series and tends to concentrate in residual solutions (Esson, J.R.) [28-30].

Arsenides are often found in the gasification products of volcanic processes. V. M. Goldschmidt discovered two types of arsenides, AsS and As_2S_3, in volcanic eruptions. W. Geilmann determined that two volcanic sulfur samples from West Java contained As of 62×10^{-6} and 9×10^{-6}, respectively. The average As content in the condensation water of the Hokkaido volcano in Japan is 0.49×10^{-6}. These constantly indicate a close relationship between As and volcanic exhalation. According to the related research, the intensity of metamorphism is inversely correlated with the As content of metamorphic rocks.

From **Tables 2a and 2b**, it can be seen that the As content of the vast majority of samples in the study area is lower than their crustal Clark value, and only the average value of the Upper Permian samples is close to the crustal Clark value. The content of As in the middle and lower Triassic series around the mining area is slightly higher than its crustal Clark value (**Figure 8**), and the content of As in some strongly altered rocks is significantly increased. This also indicates that the As content is closely related to alteration, indirectly indicating that mineralization is controlled by deep geological processes and not related to surrounding rocks.

The Se content of almost all samples in the study area is below its detection limit, which is $< 0.1 \times 10^{-6}$. This may be equivalent to the crustal Clark value of Se (0.05×10^{-6}-0.09×10^{-6}) [28,29], with only a few strongly altered rocks showing significant Se content (**Tables 2a and 2b**).

Research has shown that Se does not accumulate during the main crystallization and pegmatization stages of magma [29]. However, during volcanic eruptions and gas generation hydrothermal processes, Se undergoes a certain degree of enrichment. The post magmatic hydrothermal activity stage is the main enrichment stage of Se and Te. Based on this, the enrichment of Se in the study area seems to be related to deep geological thermal events, such as mantle plumes.

The abundance of Au in various rocks in the study area is not high, lower or close to its Clark value in the Earth's crust, i.e. 0.004×10^{-6} (**Tables 2a and 2b**, **Figure 10**), with only a few altered rocks showing significantly higher Au abundance.

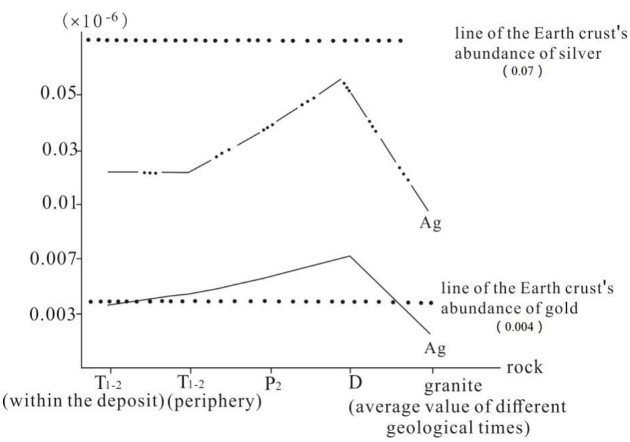

Figure 10. Comparison of Au and Ag contents in the country rocks and regional granites of different ages around the mining area.

The abundance of Au in the Devonian rocks is slightly higher than its Clark value in the Earth's crust, and the Au content is the highest in rocks of different ages in the study area. This is consistent with the fact that most of the gold deposits and gold showings in the study area occur in the Devonian system.

Ag and Au have obvious positive correlations and similar distribution patterns (**Figure 10**).

6.3 Cu, Pb, and Zn

The Clark value of Cu in the continental crust is 55×10^{-6} (Taylor, 1964) [28,29]. The Cu content of most rock types in the study area is lower than its Clarke value (**Tables 2a and 2b**, **Figure 11**). There is only one sample from the Upper Permian and five samples from the lower-middle Triassic, including 3 strongly altered rock samples containing Cu above the Clark value. This also shows that the copper content has nothing to do with the country rock itself, but is closely related to deep geothermal events such as mantle plumes.

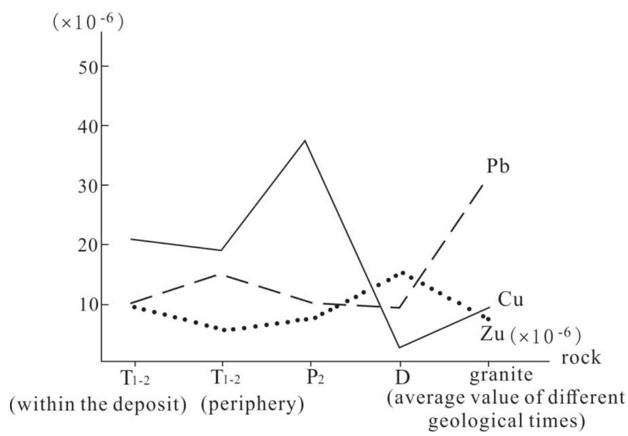

Figure 11. Comparison of Cu, Pb and Zn contents in the country rocks and regional granites of different ages.

The Clarke value of Pb in the Earth is 13×10^{-6}, and that of Pb in the Earth's crust is 10×10^{-6}-16×10^{-6} (Li Tong, 1976) [28,29]. Based on this and comparing **Tables 2a and 2b** and **Figure 11**, it can be seen that the Pb abundance of most rock types in the study area is lower than its crustal Clark value. Only the Chengjiang orogenic granites in the periphery of the mining area, and the lower-middle Triassic samples from Miaoping-Liushapo in the periphery of the mining area contain significantly higher Pb. This may be related to the nearby Guanyinshan lead-zinc mine, but has nothing to do with the lead contained in the surrounding rocks.

The Clark value of Zn in the Earth's crust is shown in **Table 3**. The Zn content of about half of the samples in the study area is greater than or close to its crustal Clark value (**Tables 2a and 2b**, **Figure 11**), and has the following distribution rules:

Table 3. The Clark value of Zn in the Earth's crust.

Researcher	Vinogradov	Taylor	Song Miao	Weidelpol
Year	1962	1964	1966	1967
Abundance ($\times 10^{-6}$)	83	70	70	60

Source: [1].

The Zn content in acidic granite is higher than that in alkaline granite.

Regardless of the mining area or the periphery, the content of Zn in the Middle and Lower Triassic ore-hosting schist is higher than that in marble, and the strongly altered schist contains higher Zn.

No matter in the mining area or the periphery, the Zn content in all kinds of dolomite veins in the study region is low.

Combining the host rock's geology, geochemistry, and previous researchers' study on REE and silicon isotope of the lower-middle Triassic rocks [1,8-10,17-19], the following preliminary conclusions can be reached:

The ore-forming elements do not originate from various rocks around the deposit. The existence of numerous basalts from different geological ages in the study area, as well as the frequent and unusually active interactions between the crust and the upper mantle, all prove from one aspect that the deposit's ore-forming elements originate from the mantle.

Previous studies on sulfur isotopes and mineral fluid inclusions have also shown that the ore forming minerals of the Dashuigou tellurium deposit originated from the upper mantle [9,10].

Its enrichment mechanism is that these substances in the nanometer level from the mantle are enriched into ore bodies through the unique nano-effect, and then were brought to the Earth's crust to settle down to form the deposit in the late Yanshanian orogeny [5,6,25].

7. Conclusions

In summary, this article draws the following conclusions:

The distribution of Te, Bi, As, Se, Cu, Pb, Zn, Au, and Ag in different rock types of different ages shows that the abundances of the main ore-forming elements Te, Bi, As, Se, Au, and Ag in the regional geological background are not high, generally lower than or close to their respective crustal Clark values. The enrichment of these elements is obviously closely related to the later alteration. The geological processes that cause this alteration and mineralization come from deep underground such as mantle plumes.

Mineralization is not achieved through horizontal or near-horizontal lateral secretion; that is, the ore-forming materials do not originate from ore-hosting wall rocks, but from deep.

The migration of deep metallogenic elements is not achieved through the diffuse infiltration between particles in the overlying formation rocks, but through non-widely distributed concentrated penetrating faults, such as the intersection of two groups of faults in different directions, or the expansion structure formed by the intersection of linear and circular structures.

Existing geophysical, geological and geochemical evidence shows that the study area located on the edge of the Qinghai-Tibet plateau is an area with an extremely active crust and upper mantle. It is both an area where geological structures including deep and large lithospheric faults are well developed and an area where mantle materials work well. It is under this very favorable geological background that the ore-forming elements such as tellurium were enriched in the upper mantle through nano-effects and then intruded along deep and large faults into appropriate parts of the crust to precipitate and form the deposit.

Author's Contributions

The whole research included in the paper was proposed and supervised by the first two authors J. Yin and S. Xiang. The chemical compositions were analyzed by the second and third authors H. Yin, H. Shi, and Y. Chao of this paper. All authors prepared and reviewed the manuscript and approved the final version of the manuscript.

Conceptualization: J. Yin; Investigation: J. Yin, S. Xiang, H. Yin, H. Shi, and Y. Chao; Project administration: J. Yin, S. Xiang; Writing—original draft: J. Yin.

Conflict of Interest

There is no conflict of interest.

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