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The Thermal and Dynamic Process of Core → Mantle → Crust and the Metallogenesis of Guojiadian Mantle Branch in Northwestern Jiaodong

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Abstract: The Jiaodong gold mineral province, with an overall endowment estimated as >3000 t, located at the eastern segment of the North China Craton (NCC), ranks as the greatest source of Au in China. The structural evolution, magmatic activity and metallogenesis during the Mesozoic played important roles in the large scale regional gold, silver and polymetallic mineralization in this area; among them, the intensive activation of fault structures is the most important factor for metallogenesis. This study takes the regional deep faults as main thread to discuss the controlling role of faults in large scale metallogenesis. The Jiaojia fault and Sanshandao faults in the northwest margin of the Guojiadian mantle branch not only are dominant migration channels for hydrothermal fluid but are very important favorable spaces for ore-forming and ore-hosting during the formation of world-class super large gold deposits in this area. The deep metallogenic process can be summarized as involving intensive Earth's core, mantle and crust activity → magmatism → uplifting of metamorphic complex → detachment of cover rocks → formation of mantle branch → penetration of hydrothermal fluid along deep faults → concentration of metallogenic materials → formation of super large deposits.

Keywords: mantle branch; metallogenesis; ore-controlling structures; metallogenic rule; ore prospecting target; Jiaodong area

1. Introduction

The Early Cretaceous' extensive magmatism and gold mineralization of the Jiaodong Peninsula, on the eastern part of the North China Craton (NCC) defining China's largest gold province, has attracted considerable attention over the last decades [1–15]. For example, Song et al. [13] summarized the deep ore prospecting results from the gold deposits in northwestern Jiaodong and discovered middle-shallow gold deposits conjunct as a whole in the deep ore. Especially for Jiaojia and Sanshandao metallogenic fracture zones, proven gold reserves have reached 1200 t and 1000 t respectively, which form two significant metallogenic belts of Jiaodong gold province.

Large-scale mineralization and its origin continue to be problematic and controversial. Based on their structural setting, mineralization style, and ore fluid geochemistry, they have been classified as (1) the orogenic gold deposit [16–23], (2) considered as world-class gold deposits as a class of unique "Jiaodong-type" gold deposits; [2,9,24], (3) the "decratonic gold deposits" [25], and the anorogenic gold deposit (e.g., intrusion-related gold deposit) [26]. Although the genesis of ore deposits is still under debate, most scholars hold that the gold deposits in these areas were caught up within the zone of a series of tectonic disturbances and over a highly perturbed mantle, according to mantle-crust movements [27–34]. Furthermore, more attention should be paid to following issues for a new prospective:

(1)   Distribution and migration of Earth's core, mantle and crust materials.

(2)   The formation and evolution of mantle plume.

(3)   The anti-gravity migration of metallogenic elements.

(4)   The concentration and positioning of metallogenic materials.

Above all, this contribution focuses on the relation between Cretaceous regional crust-mantle-core movement in Jiaodong and dynamic mechanism of large-scale gold mineralization based on successional researches and practices. Furthermore, this study mainly discusses the constraints of formation and the multiple evolutions of the mantle plume and its effects on regional gold metallogenesis.

2. Regional Geological and Metallogenetic Setting

Intensive crustal movement occurred in north China during the middle and late Mesozoic. Tancheng–Lujiang deep fault, which is called the Yisu fault in this area, also showed intensive activation. It is characterized by great horizontal and vertical extension and made great impact on multiple periods of structural movement, intensive magmatism and large scale metallogenesis [2,16,19,30,32,35–43].

The regional distribution and classification of rocks or strata often reflect the regional tectonic setting; it can be used to deduce the evolution process of regional structures. This region is located within the southeastern margin of the NCC, which is a block dominated by 3.8–2.5 Ga Archean rock units, that were significantly reworked during orogenies. The region witnessed migration and collision between the NCC and Yangtze Craton, and were temporally related to Early Cretaceous major mantle-plume activity.

Based on the summary report of the regional geological survey for Shandong province (2000), intensive structural movements and metallogenesis took place during the Cretaceous. The strata of the Cretaceous can be divided into four groups from bottom to top, which include the Laiyang group, the Qingshan group, the Dasheng group and the Wangshi group.

The Laiyang group in the lower part is composed of continental facies clastic rocks with some fold deformation, and the depression center is in the Laiyang and Zhucheng areas. The Qingshan group is a set of volcanic rocks and pyroclastic sedimentary rocks, which can be divided into three sections based on its lithology. The first and third sections are mainly composed of widely spread intermediate and acid intrusive rocks; the second section is composed of pyroclastic rocks that are obviously controlled in fracturing zones.

The Wangshi group is mainly distributed in the eastern Shandong stratigraphic division and is composed of red terrestrial clastic rocks. It generally is 2000–3000 m in thickness, the maximum is up to 3500–4000 m. In the Qingdao-Laiyang area, it interbeds with many basalt, andesite and andesitic turf, covered by thin layers of marl. Its thickness varies between 496 m and 1600 m. Both the Qingshan group and the Dasheng group belong to the middle Cretaceous, the former refers to the Qingshan group volcanic rock or intrusive rock, the later specially refers to the clastic rocks in northwestern Jiaodong. The thickness of Cretaceous volcanic-sedimentary formation in Shandong is close to, or even exceeds the thickness of sedimentary-volcanic formation (over 100 Ma) of the middle-late Proterozoic in the Jixian group.

Generally, lower and upper systems of Cretaceous rock are made up of clastic rocks, and the middle system is made up of volcanic rocks in this area. The sedimentary basin is associated with small extension and deep depression, and the dominant rocks are volcanic rocks and intrusive rocks, which demonstrates the intensive magmatic activity in that period. This is caused by the upwelling of the mantle plume and the rapid splitting and depression of the upper crust (Figure 1). At the same time, large scale gold mineralization took place, which is called "explosive metallogenesis" by some geologists [35].
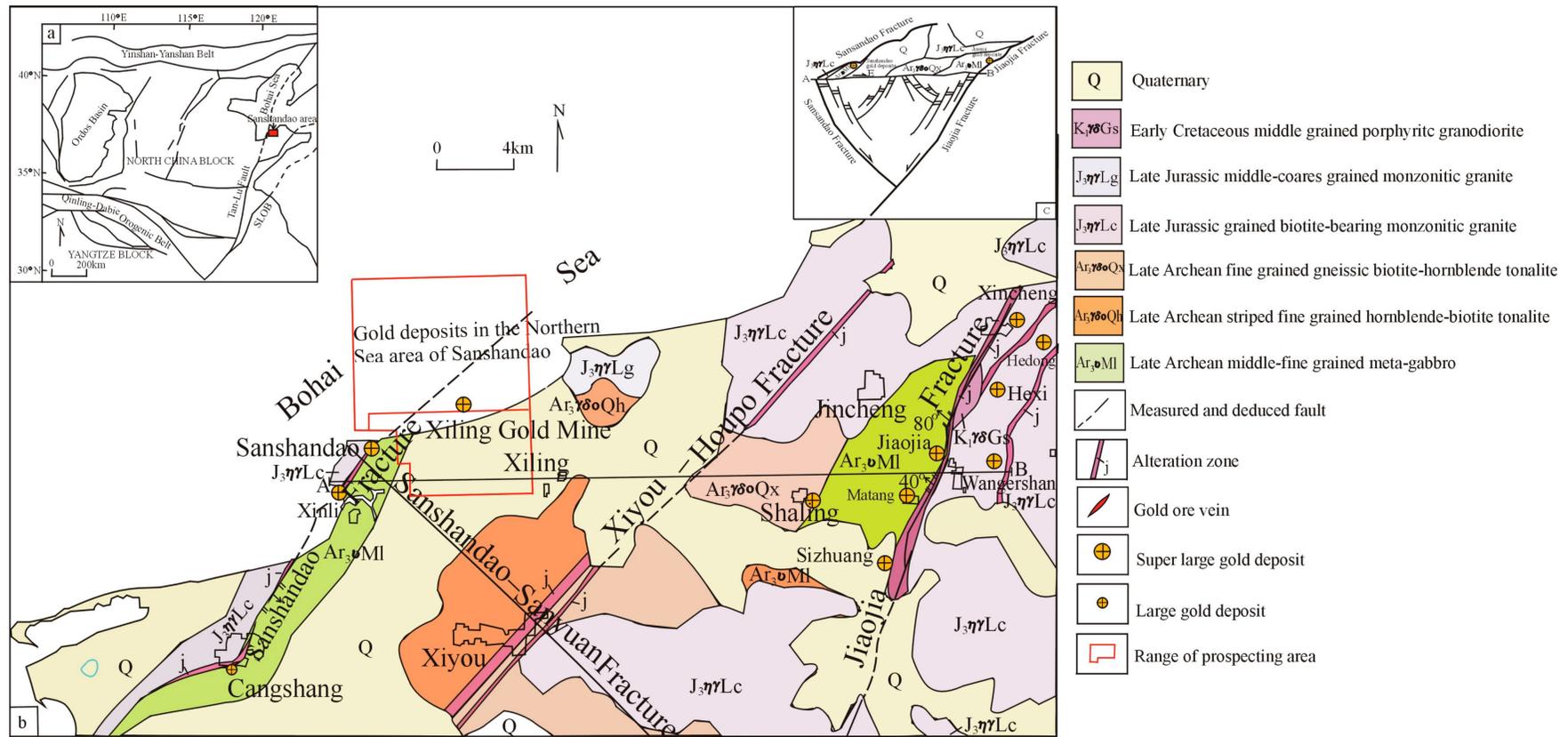
Figure 1. Geological map of the Sanshandao area. (**a**) Regional location map, from [1]; (**b**) geological map, modified after [44]; (**c**) geological structure sketch of A–B area).

3. Ore-Controlling Factors and Enlightenment of Current Prospecting Works

More than 100 large gold deposits (>20 t) and hundreds of middle-sized (5–20 t) and smaller (<5 t) gold deposits have been discovered. In northwestern Jiaodong in Shandong, which makes this area the third largest gold metallogenic area in the world. Sanshandao and Jiaojia gold deposits have become world class giant gold deposits (Table 1). Since 2017, proven gold reserves in the mining segment of north Sanshandao sea area have reached 470 t, among them, the Shaling mining segment has submitted 389 t of gold reserves [14].

The Jiaojia and Sanshandao giant gold deposits are distributed along the Jiaojia and Sanshandao fault belts, respectively. Two fault belts are nearly parallel on the surface and vertically decline in opposite direction with the stepped fault plane. Ore bodies are thickened in gently declined sections, are enriched in turning points and intersected parts of the diamond lattice faults [14,15]. Ore bodies are mainly hosted in Pre-Cambrian metamorphic rocks and Jurassic-Cretaceous terrestrial clastic rocks that have no metallogenic specificity.

3.1. The Spatial Distribution of Main Gold Ore Bodies

The ore bodies show regular distributions in Sanshandao and Jiaojia fault belts. Two gently declined ore-hosting fault benches have been exposed in both deposits. Based on the study of the spatial pattern of regional ore-controlling faults, the Jiaojia fault is the main detachment zone in the northwest margin of the Guojiadian mantle branch. The Sanshandao fault is an opposite listric fault in the hanging wall of the Jiaojia fault [45]. The relationship between the two faults, based on dynamic analysis, is that the Jiaojia fault is a backbone fault and the Sanshandao fault is a derived fault, which should be terminated on the Jiaojia fault and shows a "y-letter" spatial pattern.

The dip of main ore bodies in the Jiaojia giant deposit are same as those of the Jiaojia backbone fault. Ore bodies dip toward the northwest, and pitch toward the southwest at a 25°–30° pitch angle. The dip direction of main ore bodies in the Sanshandao giant deposit is the same as that of the Sanshandao fault. Ore bodies in the Sanshandao giant deposit dip toward the southeast, and pitch toward the northeast, the minimum pitch angle is about 35°. Both faults were sinistral strike-slip faults during the main metallogenic period; the pitch direction of the ore bodies is controlled by the strike-slip direction of the faults.

3.2. Rock-Controlling and Ore-Controlling Character of Fault Structures

There are continuously distributed 5–40 cm thick fault gouges on the main fault planes of the Jiaojia and Sanshandao faults. Most ore bodies are in the fracturing zone below the fault gouge. It is indicated that the fault gouge plays the role of a barrier layer, which makes the major ore bodies constrained below the fault gouge. Ore hosting rocks show zoning of fracturing and alteration, and they usually develop a beresitization cataclasite zone, beresitization granitic cataclasite zone, beresitization granite zone and a potassic-altered granite zone. The mineralization intensity is varied across different zones, and the major ore bodies are hosted in the altered zones [14,15].

Gold ore bodies in northwestern Jiaodong are obviously controlled by fault structures. Horizontally, the Jiaojia giant gold deposit formed in the turning part of the Jiaojia fault, which is the turning point from the South-North (SN) direction (Xuchunyuan-Sizhuang section) to the North 22.5°East-North 45°East (NNE-NE) direction (Sizhuang-Gaojiazhuangzi section). Vertically, the fault plane shows wave-shaped extension along the declined direction. The gently declined sections are usually taken as expanding spaces for the concentration of metallogenic materials. Moreover, many branch faults are developed in the foot wall of the backbone fault. The mineralization enrichment zone of the Sanshandao giant gold deposit is also in the turning part of the Sanshandao fault, which is the turn point from 80° strike (south Xinli section) to 40° strike (Sanshandao-Xinli section).

Table 1. Geological characteristics and metallogenic ages of typical Au deposits in northwestern Jiaodong.

Ore Deposit	Reserve and Grade	Wall Rocks and Intrusions and Age	Orebody and Main Metallic Minerals	Metallogenic Age	Reference
Sanshandao-Cangshang NE Ductile-Brittle Fracture Zone					
Northern sea area of Sanshandao	Au: 470 t, 4.23 ppm	Linglong gneissic granite, Guojiadian granite (zircon U-Pb 140–160 Ma); Guojialing granodiorite (zircon U-Pb 125–130 Ma)	Large veins and large lenses locally; Disseminated, einlet-reticulated pyrite-sericite cataclastic rock type ore; The main ore mineral in the ore is pyrite, followed by galena, Sphalerite, chalcopyrite, arsenopyrite, pyrrhotite, limonite, magnetite, etc.	-	[46,47]
Sanshandao	Au: >20 t, 3.40 ppm	Jurassic granite (zircon U-Pb 127 ± 2 Ma)	Flat or lenticular; Pyrite sericite type and gold-bearing pyrite sericite granitic cataclastic rock type; It is mainly pyrite, followed by arsenopyrite, chalcopyrite, galena and sphalerite, etc.	Altered Sericite Rb-Sr isochron age 117.6 ± 3.0 Ma	[48]
Xiling	Au: 383 t, 4.63 ppm	Linglong gneissic granite, Guojiadian granite (zircon U-Pb 140–160 Ma); Guojialing granodiorite (zircon U-Pb 125–130 Ma)	Large lenticular; Pyrite sericitized granitic cataclastic rocks type; pyrite, arsenopyrite, chalcopyrite, galena and sphalerite, etc.	-	[49]
Xinli	Au: 112 t, 2.78 ppm	Linglong gneissic granite, Guojiadian granite (zircon U-Pb 140–160 Ma); Guojialing granodiorite (zircon U-Pb 125–130 Ma)	Large vein-type orebodylenticular; Veinlet-disseminated pyrite-sericite cataclastic rocks type; pyrite, arsenopyrite, chalcopyrite, galena and sphalerite, etc.	-	
Cangshang	Au: 2 t, 4.93 ppm	Guojialing granodiorite (zircon U-Pb 127 ± 2 Ma)	lamellar; Pyrite sericitized cataclastic rocks type; pyrite, arsenopyrite, chalcopyrite, galena and sphalerite, etc.	Altered Sericite ^{40}Ar–^{39}Ar isochron age 121.3 ± 0.2 Ma	[50]
Longkou-Laizhou NE Ductile-Brittle Fracture Zone					
Jiaojia (deep)	Au: 73 t, 4.91 ppm	Linglong gneissic granite, Guojiadian granite (zircon U-Pb 153–160 Ma); Guojialing granodiorite (zircon U-Pb 126–130 Ma)	Stratiform and vein; Pyrite sericitized cataclastic rocks type; Pyrite, chalcopyrite, galena and sphalerite, etc.	Altered Sericite ^{40}Ar–^{39}Ar isochron age 120.5 ± 0.6 Ma; 120.1 ± 0.2 Ma; 120.2 ± 0.2Ma	[19,51,52]
Xincheng	Au: 12 t, 3.32 ppm	Guojialing granodiorite (zircon U-Pb 127 ± 2 Ma)	Lamellar, branched, compound and dilated with shrinkage; Veinlet disseminated and reticulated ores; Pyrite, chalcopyrite and galena, etc.	Altered Sericite ^{40}Ar–^{39}Ar isochron age 120.2–120.9 Ma; Beresite Rb-Sr isochron age 116. 6 ± 5.3 Ma	[51,53,54]
Hexi	Au: 13 t, 6.64 ppm	Linglong gneissic granite, Guojiadian granite (zircon U-Pb 153–160 Ma); Guojialing granodiorite (zircon U-Pb 126–130 Ma)	Lenticular, bifurcated along strike; Reticulated pyrite sericitized granitic cataclastic rock type type; Metal minerals are mainly pyrite, natural gold and bismuth tellurite, followed by chalcopyrite, galena, sphalerite, silver-gold ore, gold-silver ore, pyrrhotite, porphyry and malachite, etc.	Pyrite in ore Rb-Sr isochron age 112 Ma	[55,56]
Shaling	Au: 389 t, 2.92 ppm	Linglong gneissic granite, Guojiadian granite (zircon U-Pb 153–160 Ma); Guojialing granodiorite (zircon U-Pb 126–130 Ma)	Lamellar, and veined, branched, compound, inflated and pinched Pyrite sericitized cataclastic rocks type; pyrite, arsenopyrite, chalcopyrite, galena and sphalerite, etc.	-	[15,46]

3.3. The Constraint of the Backbone Faults on Ore Formation and Ore Controlling

Diamond lattice faults are recognized based on their different orientations and overprinting relationships, and Au mineralization occurs mainly as vein and breccia in the faults, where the regional deep fault—Jiaojia fault intersects with secondary faults (e.g., the Wangershan, the Hexi, the Houjia and the Qiujia fault). Additionally, The Sanshandao fault is a transitional part of NNE (NE) and NEE trending regional deep faults, and it controls the spatial distribution of major ore-bodies in the Changshang, Xinli and Sanshandao deposits (Figure 1).

It is obvious that ore-bodies are mainly controlled by a few ore-controlling structures. More than 180 mineralization zones have been delineated in the Shaling gold deposit with approximately 77 being economic with 389 t Au. However, the #1 and #2 are the largest ore-bodies with a 300 t gold reserve, those ore-bodies are up to >2000 m long and 1.06–125.64 m thickness.

Horizontally, the thick part of the ore body is at the southeast part of the ore body (Figure 2a). The thickness of the ore vein shows an alternative thick and thin pattern. The ore veins are branched as finger-like veins, which might be caused by the explosive hydraulic cracking of hydrothermal fluid. The grade from single engineering ore body varies between 1.00–11.37 ppm. The Au grade of bonanzas (>5 ppm) are located in the southeast part of the ore-bodies, and they also show a finger-like pattern, they are likely due to a combination of cryptoexplosion, where can be a diffusion center of ore-forming fluid. Hence, it is worthwhile to notice that some large thick ore-bodies and high grade ore-bodies in the main vein group might be caused by the pulsation cryptoexplosive metallogenesis of hydrothermal fluid.
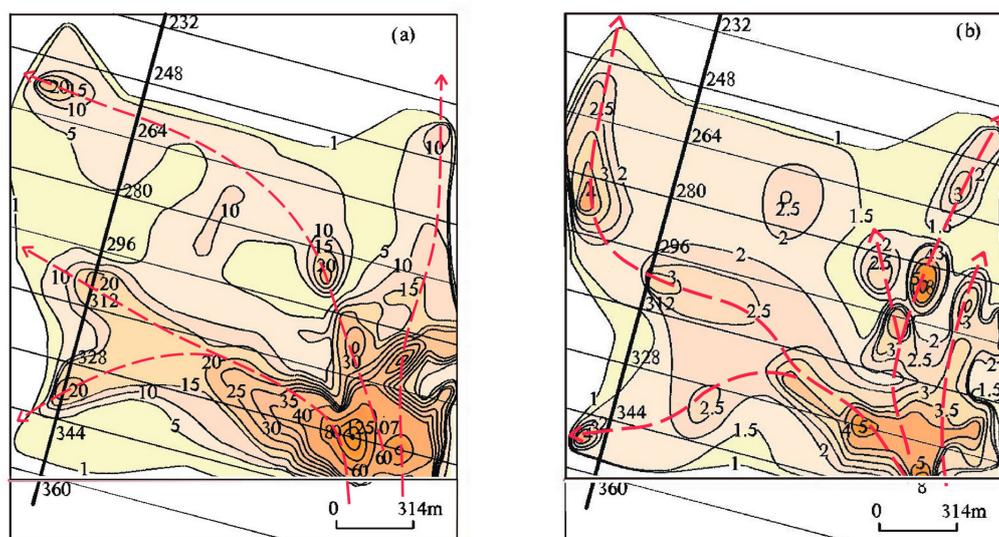

Figure 2. (**a**) Thickness isoline (unit: m) and (**b**) grade isoline (unit: ppm) for ore body I-2 in the Shaling deposit (modified after [15]). Red lines indicate the branches and extension direction of isoline.

Based on the analysis of metallogenesis of hydrothermal gold deposits, only few are mineralized in the mineralization zone, although most faults can be developed. The variation of physical and chemical conditions in deep zones can drive the ore-bearing hydrothermal fluid to migrate from deep earth to shallow crust, and some strata or rocks may stop or obstruct the migration of the hydrothermal fluid. Once the hydraulic cracking penetrates into a regional fracturing zone, the hydrothermal fluid would rapidly penetrate into the main structural zone. Because of the rapid decline of hydrodynamic pressure, the penetration of hydrothermal fluid into other secondary fractures is relatively weak, and the metallogenesis also is weak in these fractures.

Generally, if an ore concentration area develops wide migration channels for fluid, the ore-bodies will be thicker and of high grade. When hydrothermal fluid rapidly penetrates into some main fractures, penetration of hydrothermal fluid into other faults would greatly decrease because of the

variation of the physicochemical conditions of the fluid. For this reason, the reserve of main ore bodies in a deposit may occupy more than 50% of the deposit reserve, even more than 90% of the deposit reserve. In the Jiaojia, Lingnan and Taishang gold deposits, gold grade isoline is positively correlated with the thickness of the ore vein [57,58]. The closer to the fluid cryptoexplosive point, the higher the gold grade (Figure 3). This ore-forming and ore-controlling character of structure also exists in the Xiaoqinling, North Hebei and East Hebei gold deposit concentration districts.
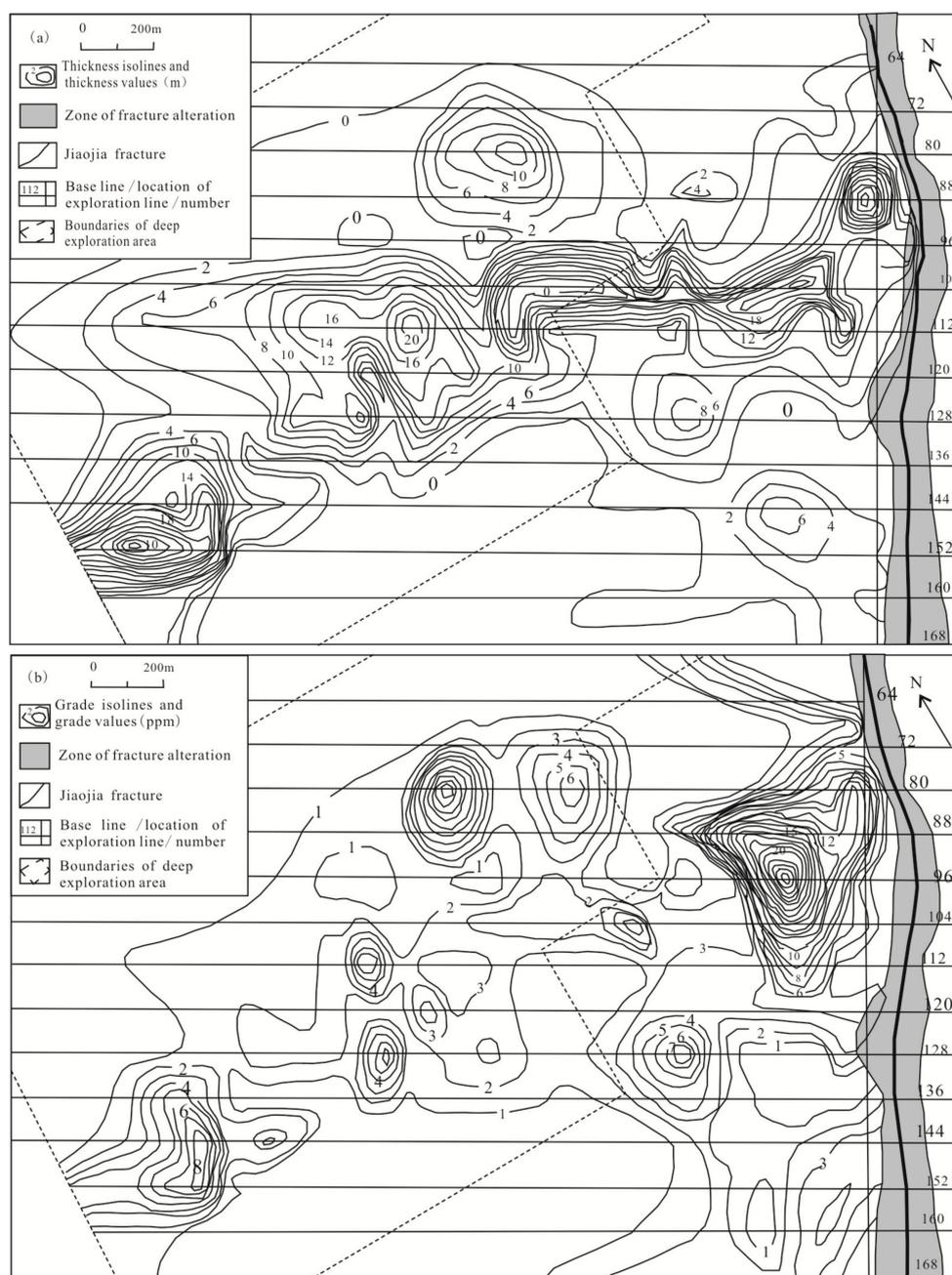

Figure 3. (**a**) Thickness isoline and (**b**) grade isoline of No.1 orebody in the Jiaojia gold deposit (from [57]).

3.4. Physicochemical Conditions of Metallogenesis

Homogenization temperature of fluid inclusions from Jiaodong gold deposits is in the range of 120–420 °C [9], most of them are concentrated in 230–320 °C [59], which is close to the metallogenic

temperature of epithermal gold deposits (generally <300 °C) in the Pacific rim metallogenic belt. So, some scholars believe that Jiaodong gold deposits belong to epithermal gold deposits [60].

The ore bodies No. I-1 and No. I-2 in the Shaling gold deposit have great vertical extension. In adjacent ore districts, ore bodies also vertically extend over 2 km, which greatly exceeds the metallogenic depth of epithermal gold deposits (<1 km). It is indicated that the metallogenic condition of Jiaodong gold deposits are obviously different from that of epithermal deposits. In recent years, many researchers also believed that the Jiaodong gold deposit is different from other known gold deposits [12,15].

Compared with previous low-temperature hydrothermal gold deposits, the spatial distribution, magnitude and physicochemical conditions (such as Temperature (T), Pressure (P), Potential of Hydrogen (Ph), Oxidation-Reduction Potential (Eh)) of Jiaodong gold deposits obviously exceed the scope of known epithermal deposits, especially for the Jiaodong middle to deep gold deposits represented by the Shaling gold deposit prospected in the past two years.

In previous studies on metallogenesis, geologists believed that regional large faults play the role of conducting ore-forming materials, and secondary faults are ore-hosting structures. More and more studies indicate that main faults usually control main ore bodies in many deposits [34]. Main faults can both conduct ore-forming materials and host ore bodies. Whether or not faults are hosting ore bodies does not depend on the scale of fault but depends on physicochemical conditions. When ore-bearing hydrothermal fluid passes through a main fault, if the physicochemical condition can not satisfy the crystallization of ore-forming materials, hydrothermal fluid would continue to migrate. In that case, main faults only play the role of ore-conducting structures; if the main faults were elevated to shallow crust with a lower P-T condition, hydrothermal fluid would have crystallized and stopped migrating before it reached shallow crust. In that case, main faults are neither ore-conducting structures nor ore-hosting structures. So, the metallogenesis of main faults does not depend on its magnitude but depends on geologic condition.

4. Mantle-Crust Evolution and the Structural Movement of Metallogenic Districts

Many geologic factors have an impact on gold mineralization [12,61–63]. Magmatic activity is the important expression of structure movement. During a period of intensive crust movement, large scale of volcanic activity or/and igneous intrusions are developed, which are accompanied with different types of metallogenesis.

Since Wilson [64] and Morgan [65] put forward the theory of hot spots and mantle plumes successively, the study of the vertical motion of the earth has been gradually strengthened [66–73] and many scholars believe that the formation of polymetallic deposits is related to mantle plumes [74–79]. But it is obvious that the scale of a mantle plume is too large for explaining the formation process of a specific deposit or ore field. The mantle branch structure which was first put forward by Professor Niu in 1996 [80–85], is the third grade of structural units during multiple evolutions of mantle plumes and is mainly used to research ore-forming and the ore-controlling role of Au-Ag polymetallic ore fields. So, in this paper, the metallogenesis of gold deposits in the Northwest of Jiaodong are discussed from the perspective of a mantle branch structure.

4.1. Mantle Uplifting and the Formation of the Laiyang Sub-Mantle Plume

Magmatic activity can be divided into large structural cycles and small pulse periods. Large structural cycles are usually related with crust movement. For instance, the structural movement and magmatism during the Yanshanian movement are divided into four cycles, and then each cycle is divided into several periods. Dominated by the intensity of structural movement, magmatic activity can express as volcanic eruption or large scale of intrusion. Based on the time and intensity of a volcanic eruption and the time and scale of intrusion, it can be divided into several periods.

Magmatism often begins with basic-intermediate volcanic eruptions and ends with intermediate-acid eruption or intrusion. When the temperature and pressure of deep magma exceed the bearing capability

of overlapped rocks, the magma would break through the rocks and bring out volcanic eruption. With the decrease of pressure, volcanic eruption would transform to intrusion [86].

During middle-late period of the Yanshanian movement, large scale magmatism occurred and a rift basin was developed in the Jiaodong area. Since the Cretaceous period, mantle magma under the Jiaolai basin showed significant upwelling, and the upper crust was rapidly extended to form the basin, which resulted in the formation of a typical sub-mantle plume. The main structural or sedimentary formation includes several geologic units: The Lower Cretaceous Laiyang group is composed of thick conglomerate, sandstone and argillaceous rocks (fluvio-lacustrine facies); The Middle-upper Cretaceous Qingshan group is composed of thick pyroclastic rocks interbedded with some terrigenous clastic rocks; the time of the Dasheng group is same as the Qingshan group, but it particularly refers to the fluvio-lacustrine sedimentary rocks in northwestern Jiaodong; The Late Cretaceous Wangshi group is made up of thick conglomerate and sandstone (fluvio-lacustrine facies). The basin takes Laiyang as its center, and it is characterized by rapid subsiding and rapid sediment accumulation. The palaeogeographic lithofacies of the whole Cretaceous can be divided into nine phases, and eight of them are in great depression. Total depression amplitude is up-to or even over 10,000 m (Table 2). Intermediate-basic dykes and intermediate-acid dykes are widely distributed in the sedimentary strata. The Guojiadian mantle branch, the Qipeng mantle branch and the Muru mantle branch are developed around the Laiyang sub-mantle plume. Generally speaking, the Qingshan period is the most intensive period of deep magmatism, and it is characterized by a short time, significant depression, intensive structure movement, thick volcanic material accumulation, a complex intrusive phase and varieties of dykes. Simultaneously, it is the most important period for metallogenesis.

Table 2. Division and correlation of Cretaceous strata in Jiaodong

Chronostratigraphy			Lithostratigraphy			Sequence Stratigraphy			Biota Radioactive Dating (Ma)	Sedimentary Environment		
Era	Period	Series	Group	Formation	Member	Grade 2	Grade 3	System				
Mesozoic	Cretaceous	Upper aeries	Wangshi geoup	Jingangkou				Ksq7	NLST	*Skacrium-Phyrsa* Mollusk fauna	Restrictedbasin	
				Hongtuya						*Protosaunus* Dinosaur fauna	River	
										68–70	Layeredvolcano	
		88 Ma				Ms4		XI		*Hadrosauridae* Dinosaur fauna	River	
		Middle series		Xingezhuang	Shijiatun basalt			Ksq6	LEST	*Viuikaruc-Skhacrium* Mollusk fauna *Yanjiestheria* Estheria fauna	Shallow lake	
				Linjiazhuang					X	LLST	*Psittacasaunue* Dinosaur fauna	River
		112 Ma	Pingshan group / Dasheng group	Fanggezhuan / Mengtuan Siqiangcun				IX	LEST LLST	90–100	Volcanic basin	Lake River
				Bamudi Shiqianzhuang / Tianjialou Malanggou		Ms3		Ksq4	LEST	*Yanjiestherla* Estheria fauna 100–110		Lake
									LLST	110–120		River
				Datuling				VIII	LEST			Lake
				Xiaodian					LLST			Rier
				Houkuang				VII	-	120–126		-
								VI				
		Lower series	Laiyang group	Malianpo / Fajiaying				Ksq3	-	Marine algae Bryozoon Foraminiferan	- Restrictedgnlf	Restrictedlake
				Chengshanhou / Dncun / Qugezhuang -				V	NLST	Nakamuranaia Bivalvian fauna	Volcanicbasin	-
				Yangjiazhaung / Longwangzhuang		Ms2		Ksq2	LCST	-	River	Shallow lake
				Shuinan					LCS	Laiyang biota		Deep lake
				Zhifengzhuang				IV	LEST	-		-
				Linsishan					LLET			
				Wawukuang				Ksq1	LEST			Deep lake
		137 Ma							LLST			-

Note: Ms—Marine flooding surface; NLST—Non-Lacustrine system tract; LEST—Lacustrine extension system tract; LLST—Lacustrine lowstand system tract; LCST—Lacustrine contraction system tract.

4.2. Pulse Upwelling of Magma and the Formation of Mantle Branches

The density (specific gravity) of mantle magma is higher than that of crust rocks. Liguliform mantle magma can emplace into low-velocity and high-conductivity middle crust and make the sandwich structure of the crust intensively deformed. Decoupled lower crust would fall down in the form of residual structural blocks. Middle and upper crust would appear as a negative gravity anomaly caused by the emplacement of intermediate-acid magma, which results in the uplifting of igneous-metamorphic complexes and the formation of a mantle branch.

The igneous rocks in a mantle branch usually evolve from intermediate-basic to intermediate-acid. When liguliform mantle magma emplaces into middle crust, high temperature mantle magma (1300–1000 °C for ultra-basic and basic magma, [87]) would melt some middle-upper crust rocks and exchange solid or liquid materials with crust rocks, which forms mantle-crust magma with a percentage of gas-liquid solution. When the energy in magma chamber accumulates enough to break through overlapped rocks, the mantle-crust magma would explosively emplace toward upper crust. When the energy is released, magma emplacement stops and the magma chamber would begin next cycle to accumulate energy until the next magma emplacement takes place. This much likes the geothermal fountain in Yellow Stone of the USA in where energy accumulation and hot water eruptions are periodically repeated. Obviously, the periodical emplacement-heat melting produces igneous complex with multiple periods of pulsation intrusion. In the middle-late period of magmatism, intermediate-acid magma occupies the majority volume of the emplaced magma. Significant negative gravity anomalies drives the metamorphosed country rocks to uplift together with igneous rocks, accompanying the detachment of cover rocks toward the surrounding area. So far, the typical mantle branch structures are formed, it has an igneous-metamorphic complex core surrounded by ring-like cover rocks and a series of normal detachment faults. The combination of the Laiyang sub-mantle plume with the Guojiadain mantle branch in the west, the Qipeng mantle branch in the north and the Muru mantle branch in the east, perfectly reflects a kind of structural combination relationship.

4.3. The Spatial Pattern of the Mantle Branch

Mantle branch theory can be used to explain the multiple pulsation intrusion process and the spatial distribution of intrusive rocks during Yanshanian magmatism. The heat circulating driven by periodical magmatic activity brought out large scale gold mineralization.

There is the Guojiadain mantle branch, the Qipeng mantle branch and the Muru mantle branch around the Laiyang sun-mantle plume. Take the Guojiadian mantle branch as an example. It developed in the west of the Laiyang sub-mantle plume. Taking the "0-value" line of gravity anomaly as a division, the outer-ring is a positive gravity anomaly area in which the anomaly value increases away from the division line. The inner-ring is a negative gravity anomaly area. Gold deposits controlled by the mantle branch are distributed along the "0-value" line. It is indicated that gold deposits were mainly formed in major and secondary detachment zones around the mantle branch.

5. Multiple Evolutions of the Mantle Plume and the Metallogenesis of Mantle Branches

In the process of the Earth's evolution, heavy elements were mainly concentrated in the core. Small amount of heavy elements (such as gold) can migrate to shallow crust through mantle plume → sub-mantle plume → mantle branch in the form of gas, gas-liquid mixture or ore-bearing hydrothermal fluid [88]. Under the impact of a regional tectonic stress field, they can penetrate into fracture zones and accumulate to form ore bodies with a variation of physicochemical conditions. The ore-forming materials mainly come from deep Earth.

Based on the non-exclusive character and the atomic structure model of gold, it is speculated that 99% gold is concentrated in the core. Gold is mixed with iron and nickel in a purple gas state within the core. In the process of intensive outer core convection and differential rotation of the core-mantle, the majority of gold gas accumulates in the core–mantle boundary (D″ layer) that is the boundary

between the core and mantle. Once the dynamic balance of the core-mantle boundary was damaged by some astronomical or intraterrestrial agents, the liquid materials in the outer-core would pass through the core-mantle boundary and migrate up in the form of a mantle plume. As a component of mantle plumes, gold gas moves up in a state of anti-gravity migration. The initial mantle plume has a small diameter and it gradually increases during its upwelling process. When it comes to the boundary between lower mantle and upper mantle, the top head of the mantle plume would be enlarged to form a mushroom-like crown because of the restriction and obstruction of the boundary. When accumulated energy in the head of a mantle plume exceeds the bearing capability of the boundary, the upwelling mantle materials would penetrate the boundary to form several sub-mantle plumes. Similarly, at the top of upper mantle, sub-mantle plume experiences same process as the mantle plume, a series of mantle branches are formed, which constitutes the typical multiple evolution sequence of mantle plumes.

Accompanied with the multiple evolution of mantle plumes, parts of gaseous gold could transform into liquid to form gas-liquid mixture when it passes through the asthenosphere. Together with the mantle methane material (CH_4), the gas-liquid mixed gold continues to migrate up with the evolution of the mantle plume [88]. In the process of upwelling of magma with a gas-liquid mixture along a deep fracture, two-thirds of the gaseous gold in mixture would enter into softened plastic country rocks, and one-third of the gaseous gold in gas-liquid mixture would experience differentiation with magmatic evolution. During the differentiation, liquid gold can directly crystallize into solid gold in near-surface freshwater environments. In surface salt water (sea water), gold migrates in a complex form, and it can aggregate into solid gold under the action of freshwater or bacteria. Table 3 shows the differential distribution of gold and silver in different spheres of the Earth.

Table 3. Distribution of gold and silver in the earth's layers [89].

The Earth's Layers	Mass Percentage of Crust-Mantle-Core (%)	Distribution of Gold			Distribution of Silver		
		Abundance ppb	Weight Ratio ppb	Volume Ratio (%)	Abundance ppb	Weight Ratio ppb	Volume Ratio (%)
Crust	0.4	3.0	1.2	0.00423	80.0	32.0	0.01005
Mantle	68.1	1.0	68.1	0.23962	55.0	3745.5	1.17495
Core	31.5	900.0	28,350.0	99.75615	10,000.0	315,000.0	98.81500
Earth	100.0	284.0	28,419.3	100.00000	3188.0	318,777.5	100.00000

Jiaodong gold deposits are characterized by their various deposit types, enormous gold reserves and rapid metallogenic process. It is necessary to study metallogensis and the metallogenic rule, conclude the metallogenic model and summarize metallogenic laws in order to guide a new round of gold prospecting works.

5.1. Heat Migration Ore-Conducting and Ore-Forming of Sub-Mantle Plumes

Traditional gold geological survey works pay much attention to looking for metamorphic rocks and granitic rocks with a high gold background value. Their theoretical idea for gold mineralization is that gold comes from the high background value country rocks and the gold is extracted from country rocks and accumulated into favorable structures as ore bodies under the impact of magmatism and structure movement. Based on the above idea, gold migration is from low P-T environments to high P-T environments and from low grade rocks to high grade rocks, this is difficult to realize in normal geological conditions [90].

From the viewpoint of the multiple evolutions of mantle plumes, heavy elements such as gold and silver mainly come from the boundary between the core and mantle. Through multiple evolutions of the mantle plume, they penetrate the major structural expanding zones of mantle branches in the shallow crust. In that case, ore prospecting work should follow the system of sub-mantle plume–mantle branch–structural expanding zone–ore-hosting fractures (Figure 4).
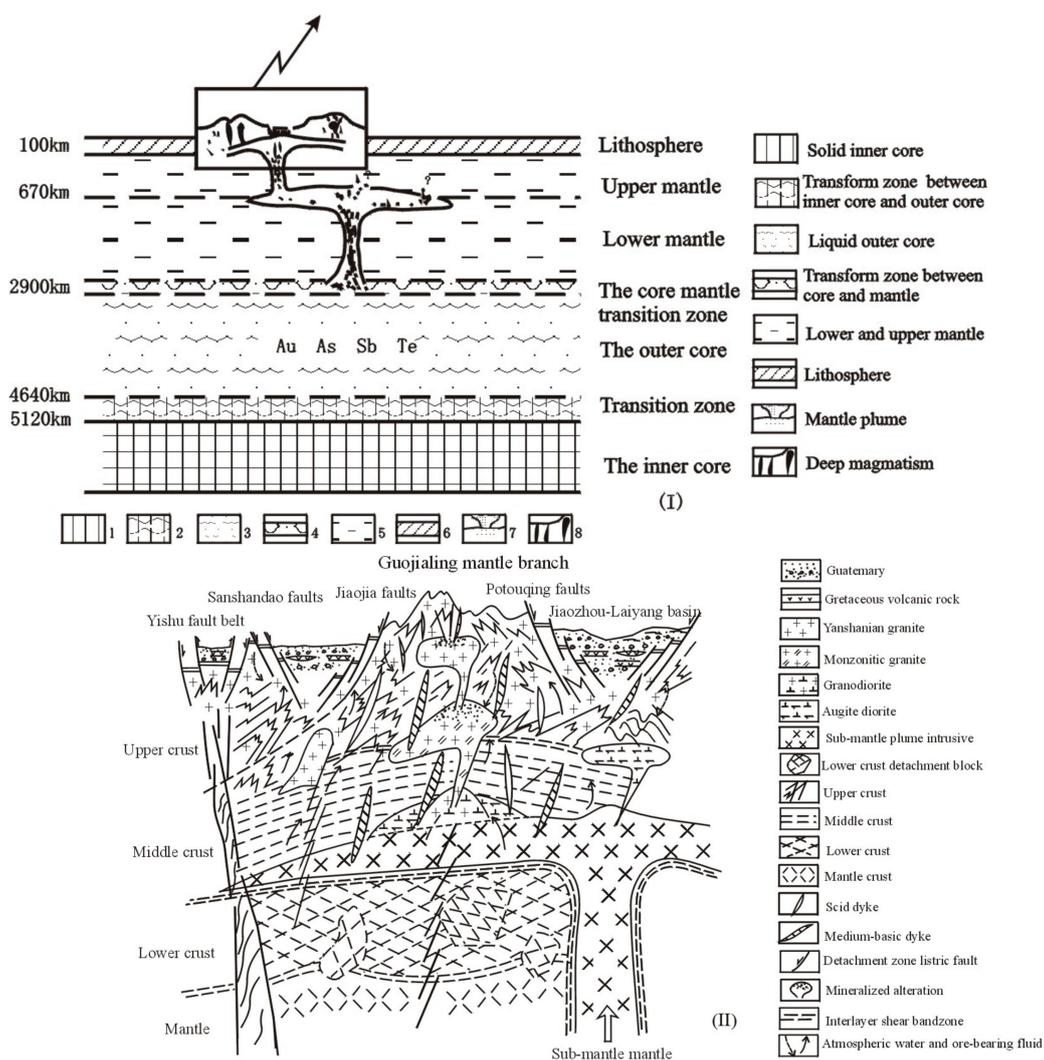
Figure 4. Sub-mantle plume-mantle branch evolution and its metallogenesis: Mantle plume-sub-mantle plume mode (**I**) and Sub-mantle plume-mantle branch metallogenic mode (**II**).

The sub-mantle plume is the secondary structure unit of a mantle plume, and it plays the role of connecting the lower mantle and the upper crust. It also is the pathway for magma to migrate from deep earth to shallow crust, and the main place for energy to accumulate and release. The pulsation of magmatic activity, energy release and accumulation, is much like the geothermal springs of Yellowstone Park in the USA. Intermittent igneous intrusion or eruptions produce multiple-phases of complexes. Early eruption and intrusion are dominated by intermediate-basic magmatic activity; late magmatic activity which evolves to intermediate-acid magma.

With the rapid uplifting of a sub-mantle plume, a large scale faulted subsidence basin rapidly forms above the top of the sub-mantle plume. The basin has a mirror symmetry relationship with the sub-mantle plume. Intense activity and large uplifting amplitudes of deep mantle magma are usually accompanied with a rapid fault basin development, large influence dimension and significant depression in the shallow crust. This shows a gravity equilibrium compensation in relation with deep mantle uplifting.

The Laiyang basin is a fault basin formed rapidly on the top of a sub-mantle plume. It developed in the Cretaceous and was widely spread in the Laiyang stratigraphic district which includes the Jiaolai basin and its surrounding elements. Sedimentary formation is composed of inland basin fluvio-lacustrine clastic rocks interbedded with terrestrial pyroclastic rocks that are overlapped non-conformingly on an ancient metamorphic basement. It is divided into the Laiyang group, the

Qingshan group and the Wangshi group, from bottom to top [58]. The Laiyang group exhibits obvious horizontal variation and a differential diagenetic environment, and it is made up of terrestrial clastic rocks interbedded with some volcanic rocks. The Qingshan group is widely spread in the Jiaolai basin and its surrounding elements. It is a set of terrestrial volcanic rocks and pyroclastic rocks formed in a volcanic basin. The rock formation includes dactitic pyroclastic rocks → andisitic-basaltic andesitic lava and pyroclastic rocks → rheolitic pyroclastic rocks and lava → trachytitic andesitic lava interbedded with pyroclastic rocks, from bottom to top. Subvolcanic intrusions were developed in each period of volcanic activity. The Wangshi group is distributed in the Jiaolai basin and its western elements. It is mainly distributed in Laixi, Laiyang and Jiaozhou in the Jiaodong area, especially in Laiyang. It is much same as molasses formations made up by a set of red terrestrial clastic rocks interbedded with some volcanic rocks.

Overall, above mentioned sedimentary formation in the Laiyang basin indicates that intensive structural movement during the Cretaceous had wide distributions and deep extensions. At the same time, large scale of metallogenesis took place in that time.

5.2. The Ore-Forming and Ore-Controlling of Mantle Branches

Geodynamics indicate that upwelling mantle magma from sub-mantle plumes comes to the surface or shallow crust in the form of volcanic eruptions or intrusions. Constrained by regional structural stress fields, magmatic activity shows alternative variations of intense and weak, large volume and small volume, eruptions and intrusions. The uplifting and evolution of magmatic-metamorphic complexes results in a series of mantle branches.

The crust has an obvious sandwich structure, and different layers show different characters. The upper crust is shallow and cold; the lower crust is deep and rigid; the middle crust is heat softened layer. The regional ductile shearing zones in the crust constrain the structural movement and magmatism. The density (specify) of mantle magma is much higher than that of the middle crust. The existence of detachment zones in the crust makes it easy for the mantle magma intrude into detachment zone in a large tongue shape. Because the tongue-shaped mantle intrusion could detach the sandwich structure of the middle-lower crust, parts of residual crust blocks would drop into the mantle magma. Meanwhile, the upwelling of the mantle magma results in faulting and subsiding of the upper crust, forming a fault basin controlled by listric faults around the basin margin.

With the increase of depth, the temperature and pressure of crust increases gradually, which causes the deep crust rock to be softened. Intruded high temperature mantle magma (1300–1000 °C for ultra-basic and basic magma) would heat and melt some crust rocks to form magma chambers that are filled with mantle-crust magma with a percentage of gas-liquid solution. The periodical energy accumulation and release in the magma chamber causes pulse eruptions or intrusions. The country rocks of magma chamber are progressively heated, so the temperature for melting country rocks decreases and the crust material in magma gradually increases. So, igneous rocks usually show the evolution sequence of basic → intermediate-basic → intermediate-acid → acid.

When the intermediate-acid igneous rocks reach a certain volume in the magmatic complex, a negative gravity anomaly would drive metamorphic country rocks to uplift together with the magmatic rocks, forming the magmatic-metamorphic complex in the core of the mantle branch. The uplifting of magmatic-metamorphic complexes either provides a connection for a sub-mantle plume and mantle branch or creates a migration channel for deep ore-bearing fluid and favorable structural expanding spaces for metallogenesis.

5.3. Mantle Branch Metallogenesis and Its Main Types of Mineralization

As mentioned above, once the mantle plume evolution links the crust to deep source, especially to the core-mantle boundary, the source material in the D″ layer would migrate up through the mantle plume → sub-mantle plume → mantle branch and concentrate to form a deposit in a favorable structural expanding zone of the mantle branch. These favorable structural expanding spaces include

the brittle-ductile detachment zone in the core of the mantle branch, the contact zone between intrusion and country rock, the contact zone between metamorphic complex and cover rocks, faults and joints formed in the process of mantle branch uplifting. Different structural spaces result in different structural metallogenic types.

The core of the Guojiadian mantle branch (Linglong-type gold deposit): It mainly refers to the vein ore bodies in the core uplifting zone between the Jiaojia fault and the Potouqing fault. Ore bodies are hosted in Linglong granite and some metamorphic rocks. Fractures are well developed within ore-bearing geological bodies between the Jiaojia fault and the Linglong fault. The deposit type belongs to structural fracture veins. Ore veins are densely developed, and their gold grade is high. It is a major ore-forming and ore-controlling structure type in Jiaodong [14].

Detachment zone in the northwest margin of a mantle branch (Jiaojia-type gold deposit): The Jiaojia fault is a dominant ore-forming and ore-controlling structure in the northwest margin of the Guojiadian magmatic-metamorphic core complex. The fault has both great horizontal extension and vertical extension. It not only is a regional ore-conducting structure, but an important ore-forming and ore-controlling structure. Deposits controlled by this fault are the most famous fracture alteration gold deposits in Jiaodong. Recent ore prospecting works indicate that the vertical extension of ore bodies is usually larger than their horizontal extension. Previous proved gold deposits such as the Shizhuang deposit, the Matang deposit, and the Jiaojia deposit connect as a whole deeper down, which forms an ultra-large gold deposit. Deep prospecting works indicate that ore bodies show stable extension along the fault, which provides great prospecting potential for this gold deposit [14].

Sanshandao reverse listric fault belt (Sanshandao-type gold deposit): Recently, prospecting works for the Sanshandao metallogenic zone have made much progress. Viewing from metallogenesis, it is an ultra-large fracture alteration gold deposit that is strictly dominated by a reverse listric fault [13,44]. The giant gold mineralization zones, named the Sanshandao giant gold deposit, have been delineated in Sanshandao with several larger gold ore-bodies, which are thought to be an independent deposit previously [15].

Peripheral faults of a mantle branch (Pengjiakuang-type gold deposit): Due to the rapid splitting of the Laiyang fault basin, the structural contact belts around the Laiyang fault basin are developed between the Guojiadian mantle branch and the Laiyang fault basin. A certain thickness of ore-bearing conglomerate has developed in the structural contact belts. Studies indicate that conglomerate distribution belts are usually weak structure belts for ore-forming and ore-controlling, and they easily form typical conglomerate-type gold deposits.

Mantle branches mainly form under a tectonic setting transformed from regional compression to regional extension. A core complex, marginal main detachment zones, hanging wall cover rocks and related fault structures are the components of the mantle branch. The detachment zones and related faults are usually taken as main structural expanding zones for metallogenesis. Studying the fault distribution and ore-bearing potential, metallogenesis, metallogenic modes and metallogenic rule of mantle branches is important for guiding the next round of ore prospecting.

6. Conclusions

The Jiaodong mineralization concentration area is characterized by its large metallogenic scale, deep ore body extension, high ore grade, variety of deposits and great resource potential.

(1) The multiple evolutions of mantle plume break the restriction of earth spheres (core, mantle, crust) structure, and provide an important channel for deep ore-forming material to migrate up. The study on the multiple evolutions of mantle plume elaborates the migration mechanism of heavy elements migrating from the core to shallow crust.

(2) In the process of mantle plume multiple evolutions initiated from core-mantle boundary (D″ layer), heavy elements (such as gold and silver) which sank into the core by gravity differentiation migrate up in the form of a gas-liquid state. They are concentrated to form ore bodies in the

favorable structural expanding zones in mantle branch and different fractures. Ultra-large gold deposits with huge reserves can be formed.

(3) Metallogenic material came from deep earth and accumulated as ore-bodies in favorable structural expanding zones. Generally speaking, a favorable fault is not necessary to form deposits, but ore-bearing fault structure is linked to the deep earth. Favorable fault structures can be either migration channels for metallogenic material or hosting places for ore bodies.

(4) Structure movement, magmatism and metallogenesis are critical factors in the mineralization of large metal deposits. The structure movement is the most important factor in igneous activity related to gold metallogenic events. In the Jiaodong area, the main faults play both roles of fluid migration channels and ore-hosting places, forming large to ultra-large gold deposits.

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