Isotope Geochemistry of Gold Ore Deposits in the Gezhen Shear Zone, Qiongxi, Hainan Island *

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Abstract: Gold deposits hosted in the Gezhen shear zone at Qingxi, Hainan Island occur in the Precambrian metamorphic rock series and are regionally developed in the N-E direction along the tectonic zone. From northeast to southwest are distributed the Tuwaishan-Baoban gold mining district, the Erjia gold mining district and the Bumo gold mining district, making up the most industrially important gold metallogenesis zone on the Hainan Island. Isotope geochemical studies of the typical gold deposits in this metallogenesis zone indicate that their ore-forming materials stemmed largely from the Baoban Group migmatite series, though the involvement of some plutonic materials could not be ruled out. The ore fluids are the mixture of migmatitized hydrothermal solutions and meteoric waters in addition to the involvement of local magmatic hydrothermal solutions. The superimposition of plutonic materials and magmatic hydrothermal solutions is controlled by the deformation environment of the shear zone and later magmatic activities. Obvious variations are noticed in isotopic composition in the region studied, probably related to tectonic deformation, metamorphism and other evolutionary characteristics. This study is of great significance in understanding the relationship between the shear zone and gold metallogenesis, the rules of gold metallogenesis and gold ore prognosis.

Key words: isotope geochemistry; gold deposit; shear zone; Hainan Province

1 Geology

Gold deposits controlled by the Gezhen shear zone at Qiongxi occur in the contact zones of ocular-laminated migmatites and migmatitized mica-quartz schists, prophyllites, etc., as well as in their inside parts, in the Baoban Group metamorphic rock series (Fig. 1). Lithological characteristics and isotopic ages (zircon U-Pb isotope apparent ages: $^{206}Pb/^{238}U = 1.24 \times 10^9 a$, $^{207}Pb/^{238}U = 1.34 \times 10^9 a$, $^{207}Pb/^{206}Pb = 1.49 \times 10^9 a$)①, permit us to designate the rocks to the Middle Proterozoic. Their protoliths are a suite of detrital sediments and intermediate-basic volcanic rocks and tuffaceous rocks. As viewed from the high contents of gold in the strata, high variance values and the increasing trend of gold contents from high-grade to low-grade metamorphic rocks, it is deduced that the Baoban Group provided at least part of the gold and other ore-forming materials.

The major N-E-extending structure—the Gezhen shear zone cuts across the whole region and controls the metallogenesis of the Tuwaishan, Baoban, Erjia and Bumo gold deposits. This shear zone is characterized by multi-episodic tectonic activities, as represented by ductile- or brittle-duc-

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① Hainan Gold Ore Research Team under the Institute of Geochemistry, Chinese Academy of Sciences, 1990, A preliminary exploration of several geological problems of the Erjia gold deposit in Hainan (a brief report).

tile nature in the early period and by ductile-brittle or brittle nature in the late period. In space the upper part possesses ductile-brittle or brittle characteristics, in going further downwards the ductile characteristics tend to become more and more obvious. Additionally, the exposed northeastern portion of this shear zone is characterized by a brittle-ductile deformation environment and the southwestern portion by a ductile-brittle deformation environment. This may explain why there is some difference in metallogenesis of gold from northeast to southwest.

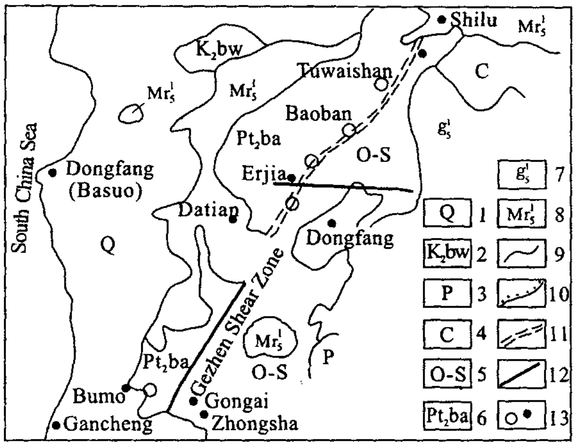

Fig. 1. Regionally geological sketch map of the Gezhen gold ore zone. 1. Quaternary clayey sand and sandy gravel; 2. Upper Cretaceous Baoban Group shale and sandy conglomerate; 3. Permian crystalline limestone and metamorphic sandstone; 4. Carboniferous metamorphic sandy conglomerate and crystalline limestone; 5. Ordovician-Silurian metamorphic siltstone, phyllite and schist; 6. Middle Proterozoic Baoban Group migmatite; 7. Indo-Sinian granite; 8. Indosinian migmatic granite; 9. geological boundary; 10. unconformable boundary; 11. mylonite zone; 12. fault; 13. gold deposit (prospect).

The main types of gold deposits in the region studied include the altered mylonite-type and the quartz vein-type gold deposits. The former type is distributed in the center of the mylonite zone. Gold deposits of this type are large in scale, the orebodies are composed of altered mylonite or silicified quartz core and show no clear-cut boundary with the country rocks. The latter type occurs as fillings in the fissure system associated with shearing, the orebodies are very simple in form and usually occur as individual dykes or lenses or ore veins. The ores are simple in composition. In accordance with the mineral assemblages and ore textures and structures, the hydrothermal mineralization of gold processes can be divided into three stages: (1) the quartz-pyrite-arsenopyrite stage, during which gold-poor coarse-grained hypidiomorphic-idiomorphic arsenopyrite and pyrite were formed; (2) the quartz-polymetallic sulfide-native gold stage, which is the main mineralization stage during which fine-grained or fine-veined arsenopyrite, pyrite and micro-grained quartz, as well as minor amounts of galena, sphalerite and chalcopyrite were formed, associated with precipitation of native gold in large amounts, with electrum seen locally. In addition to quartz, there are some other gangue minerals, including sericite and chlorite; (3) the calcite-quartz stage, during which the minerals formed usually contain no gold and minor sulfide minerals can be seen. The wall-rock alterations associated with metallogenesis are silicification, pyritization, sericitization, chloritization and carbonatization.

2 Sulfur isotope geochemical characteristics

In the gold deposits of the Qiongxi shear zone the sulfides closely associated with metallogenesis are mainly pyrite and arsenopyrite. Shown in Fig. 2 are the results of sulfur isotopic measurement of pyrite and its compositional variations in the ores and wall rocks such as migmatites and metamorphic rocks in the typical mining districts. The results of sulfur isotopic measurement of a few arsenopyrite samples show similar characteristics of pyrites, whose $\delta^{34}S$ values vary between 3.78‰ and 6.80‰. From the above we can acquire the following rules.

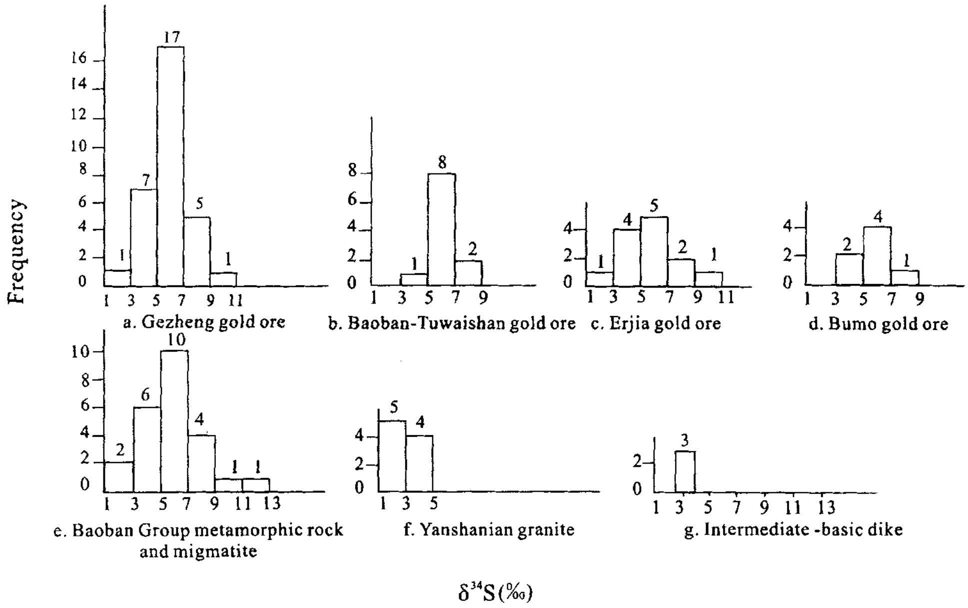

Fig. 2. Histograms of sulfur isotopes in pyrites from ores and rocks in the Gezhen gold zone (f from Zhang Ligang, 1985; g from Feng Lianshun, 1988).

(1) The sulfur isotopic composition characteristics of ore pyrite are in good consistence with those of pyrite from the Baoban Group migmatite and metamorphic country rocks, but are significantly different from those of Yanshanian granites and some intermediate-basic dykes. The sulfur isotopic values of ores and the Baoban Group metamorphic rock series are all of normal distribution, with the peak values very close to one another, and $\delta^{34}S$ values are within the range of 6‰ – 7‰ for the ores and 5‰ – 6‰ for the metamorphic rock series, reflecting that the ore sulfur isotopic composition is controlled by the background values of the country rocks and the ore sulfur stemmed mainly from the Baoban metamorphic rock series, and the Yanshanian granites and intermediate-basic dykes would not be probably the main contributors of ore sulfur.

(2) The ores are characterized by a small variation range of sulfur isotopic values, enrichment in ^{34}S, and the $\delta^{34}S$ values for the whole ore zone are within the range of 1.85 ‰ – 9.76‰ with a range of 7.91‰ and the peak values ranging from 6‰ – 7‰, as observed in the various ore deposits. In addition, the average $\delta^{34}S$ values are very close to each other: 6.24‰ in the Baoban-Tuwaishan mining district; 5.86‰ in the Erjia mining district; and 5.83‰ in the Bumo mining district, reflecting a relatively simple source of sulfur for the whole ore zone.

(3) Pyrite-arsenopyrite cogenesis is a common phenomenon encountered in the ores and the two minerals, especially pyrite, occupy a major portion of the ores. Barite and other sulfates are absent, probably reflecting that the oxygen fugacity (f_{O_2}) in the metallogenic system is low, with reduced sulfur being dominant. So, the average $\delta^{34}S$ values of pyrite could approximately represent the sulfur isotopic composition of the metallogenic system (Luan Shiwei, 1987). The ^{34}S values of ores and country rocks are very close to each other, indicating that sulfur in the ore-forming system had not undergone intensive fractionation and that the oxygen fugacity and pH in the ore-forming setting are not so high (Ohmoto, 1972; Ohmoto et al., 1979).

(4) As shown in Fig. 3, from the early to late metallogenic stages, the $\delta^{34}S$ values of pyrite tend to decrease drastically. For instance, in the Baoban-Tuwaishan mining district the $\delta^{34}S$ values of pyrite vary from 8.22‰, 6.27‰ to 4.01‰; in the Erjia mining district, 7.66‰, 5.53‰ to 3.40‰; and in the Bumo mining district, no $\delta^{34}S$ values of pyrite formed in the first metallogenic stage have been acquired. But, from the second to third stages, similar variations in $\delta^{34}S$ are observed, from 6.44‰ to 4.30‰. According to Ohmoto (1972) and Ohmoto et al. (1979), this phenomenon implies that the sulfur isotope fractionation is predominantly controlled by the two factors f_{O_2} and pH. This reflects in the process of evolution of the hydrothermal solutions from early to late the oxygen fugacity tends to increase and the pH value tends to decrease. Such changes in ore-forming conditions are in consistence with the transformation trend of the shear zone from ductile to brittle in nature, revealing the influence of tectonic activities on metallogenesis.

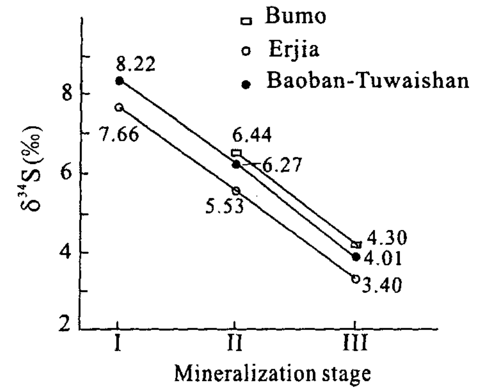

Fig. 3. Sulfur isotopic variations of pyrite in different metallogenic stages.

3 Lead isotope geochemical characteristics

Lead isotopes are usually called the tracer elements and they bear much information about the source of ore-forming materials and the history of metallogenesis and evolution. Measurements of Pb isotopes in ores and rocks, as well as whole-rock samples (Fig. 4) indicate that the data points of Pb isotopic composition of rocks are linearly plotted in the $^{208}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ diagram (Fig. 4), falling near the same line. Fitting this line with the least square method, the following ideal linear equation can be acquired:

$$^{207}Pb/^{204}Pb = 0.0927 \times {}^{206}Pb/^{204}Pb + 13.8586$$

This line intersects the Stacey's evolution curve (Stacey and Karamers, 1975) at the point where $^{206}Pb/^{204}Pb = 15.761$ and $^{207}Pb/^{204}Pb = 15.320$, with the age of 1.70×10^9a at the intersecting point, close to the zircon U-Pb age of the Baoban Group (1.49×10^{-9}a). It is clear that the age is indicative of the characteristics of initial lead in the Baoban Group and represents its forming age. The line reflects the characteristics of accumulation and evolution of radiogenic lead after the formation of the Baoban Group.

Ore lead isotopic composition is generally characterized by high radiogenic Pb, significantly varying $^{206}Pb/^{204}Pb$ ratios and a relatively narrow range of $^{207}Pb/^{204}Pb$ variations (Fig. 4). As compared with the plumbotectonic model evolution curve (Ohmoto et al., 1979; Zartman et al., 1981), the data points fall near or above the upper crust evolution line, with part of the data points against the orogene evolution curve and individual points falling near the mantle evolution curve. So, it can be seen that the source of ore lead in this ore zone is very complicated, i.e., ore lead comes predominantly from the shallow-source orogenic belt and partly from the superimposition of deep-source materials. Therefore, no significant difference is noticed in ore lead isotopic composition from one deposit to another.

As also can be seen in Fig. 4, the data points of lead isotopic composition of pyrite in the dio-

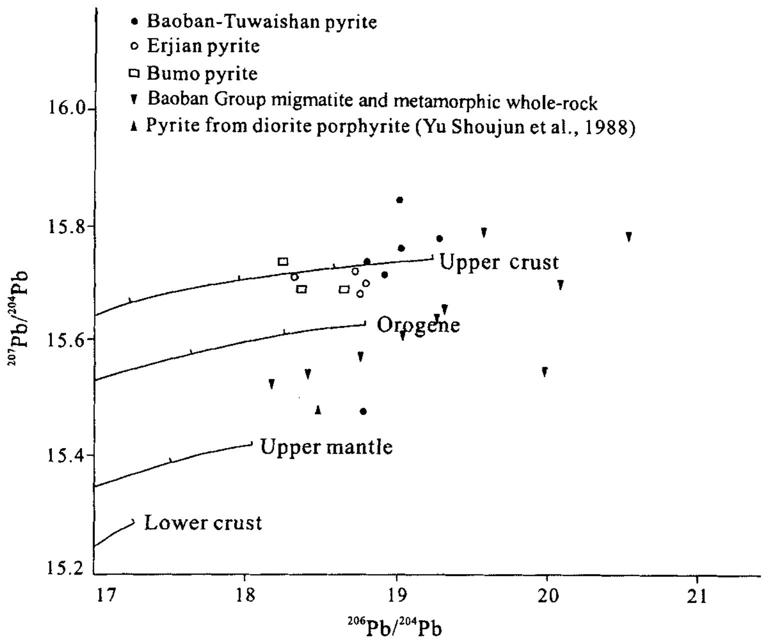

Fig. 4. Lead isotopic composition diagram of ores and rocks (the Pb evolution curve in the figure from Zartman and Doe, 1981).

rite porphyrite fall below the orogene evolution curve, close to the mantle evolution curve, reflecting the characteristics of deep-source lead.

As viewed from the relationship between lead and sulfur isotopic compositions (Fig. 5), it is found that $^{207}Pb/^{204}Pb$ has a good positive correlation with $\delta^{34}S$. This indicates that lead and sulfur in the pyrite must have been transported and precipitated from the same solution. Insignificant variations in both Pb and total S isotopic composition of pyrite can indirectly indicate they (metallic substances and sulfur) stemmed from the same source and evolutionary environment, thus lending support to the understanding that the ore-forming materials stemmed predominantly from the Baoban Group.

On the basis of the lead isotope tracing and age data in combination with the regionally geological background data, it can be concluded that the formation of gold deposits in this region underwent a multi-episodic evolution process, and gold is derived predominantly from the Baoban Group, of which the Middle and Late Proterozoic strata were enriched, to some extent, in gold, and in the later processes of metamorphism, migmatization and magmatism gold in the strata was remobilized and then transported to the favorable tectonic loci where it was further enriched as gold ores. Additionally, superimposition by later hydrothermal activities made gold from the deep-source and other sources incorporated into the strata where it was further mobilized and enriched to form gold ores.

4 Hydrogen and oxygen isotope geochemical characteristics

On the basis of oxygen isotopic analyses of the gangue mineral quartz and hydrogen isotopic analyses of its fluid inclusions and making use of the quartz-water oxygen isotope equilibrium equation

[Matsuhisa, 1979 (from Zhang Ligang, 1985)], we have acquired the $\delta^{18}O$ and δD values of the ore-forming solutions, which fall within the mixing field between meteoric water, metamorphic water and magmatic water on the $\delta^{18}O$-δD diagram (Fig. 6), revealing the ore-forming fluid may be the mixture of various sources or the outcome of their superimposition. This ore-forming fluid seems to be similar to that involved in the mineralization of gold deposits in the East Shandong area of our country.

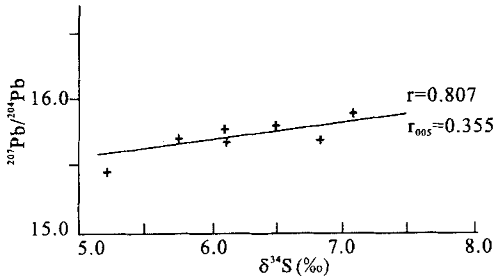

Fig. 5. Plot showing the relationship between sulfur and lead isotopic compositions of pyrite from the ores.

According to the $\delta^{18}O_{H_2O}$ and δD values of different geological bodies in the ore zone, we can see clearly that gold metallogenesis in this gold ore zone from early to late follows the order of migmatite→ore→quartz which filled in the extensile veins during the late stage in the Gezhen shear zone; from the early to late stages of hydrothermal metallogenesis the δD values of quartz fluid inclusions are obviously increased whereas the $\delta^{18}O$ values are decreased, both approaching to those of modern meteoric waters in Haikou. These hydrogen and oxygen isotopic characteristics show that the ore-forming solutions in this ore zone appear to have resulted from the mixture of hydrothermal solutions inherent in the δD-low and $\delta^{18}O$-high migmatites and δD-high and $\delta^{18}O$-low meteoric waters. With metallogenesis proceeding from early to late in time and from the deep strata to the shallow strata in space, meteoric waters tend to increase in volume. In addition, magma hydrothermal activities would have some influence on metallogenesis, thus leading to the deviation of some isotope data from the rules described above. That is to say, in case the δD values are relatively high, the $\delta^{18}O$ should be relatively high, too; the projecting points should be closer to the field of magma hydrothermal solutions. However, this phenomenon is particularly attractive in the Baoban-Tuwaishan mining district.

5 Discussion of the metallogenesis of gold

5.1 Source of ore-forming materials

The sulfur and lead isotopic composition of various geological bodies in the ore zone reflects that the ore-forming materials are derived predominantly from the Baoban Group migmatites and migmatitic rocks.

5.2 Source of ore-forming hydrothermal solution

It is considered from the hydrogen and oxygen isotopic composition of geo-fluids that the ore-forming hydrothermal solutions were derived from the mixture of migmatitized hydrothermal solutions and meteoric water-derived hydrothermal solutions.

5.3 Gold metallogenesis and metallogenic prognosis

Gold metallogenesis in the ore zone has a close bearing on the tectonic activities of the Gezhen shear zone. Multi-episodic activities in this shear zone resulted in the multi-episode gold metallogenesis. Differences in nature of the tectonic activities during different stages led to the precipitation of

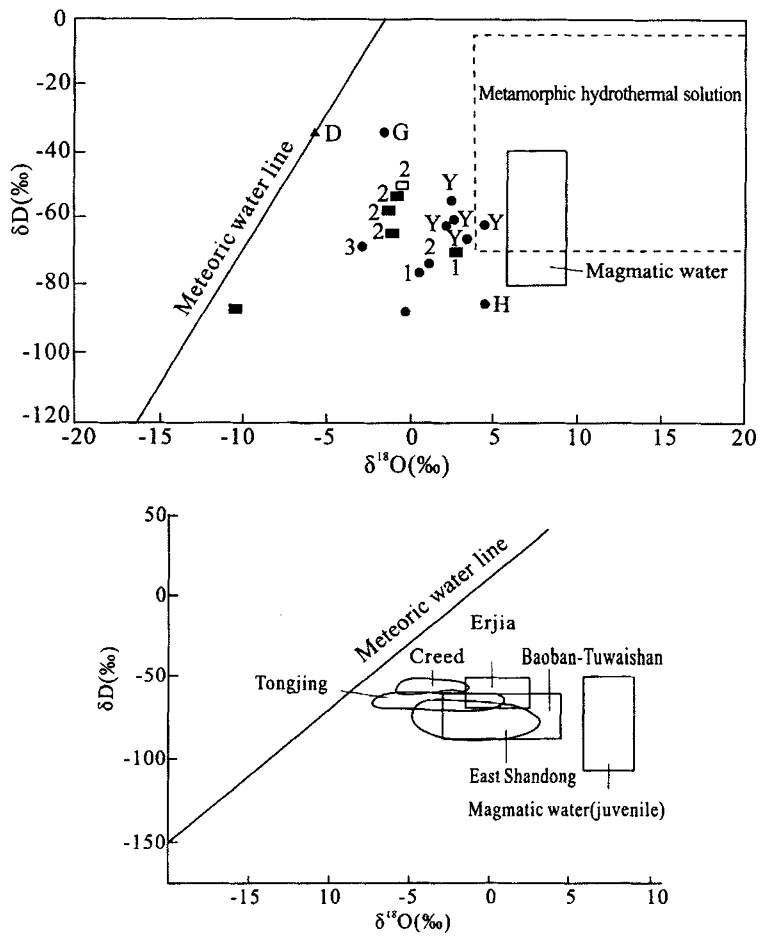

Fig. 6. Hydrogen and oxygen isotopic composition of ore-forming fluids for the gold deposits in comparison with the selected meteoric water hydrothermal gold deposits (Zhang Ligang, 1985). ⊙ Samples were collected from the Baoban-Tuwaishan mining district; □ samples collected from the Erjia mining district. H. migmatite sample; G rock samples from the Gezhen fault zone; D. modern meteoric water samples from Haikou (from Zhang Ligang, 1985); Y. from Feng Lianshun, 1988; Yu Shoujun, 1988; 1, 2, 3 represent the metallogenic stages.

ore-forming materials in large amounts. As reflected by the isotopic compositional characteristics, from early to late the tectonic activities tend to transform from ductile to ductile-brittle and brittle in nature, $\delta^{34}S$ values tend to decrease, δD and $\delta^{18}O$ values change from almost the δD and $\delta^{18}O$ values of migmatitized hydrothermal solutions to almost those of meteoric water-derived hydrothermal solutions, i. e., the ore-forming conditions change from closed to sub-closed. Under such circumstances, changes would also take place in physicochemical conditions. These are the essential factors leading to the precipitation of ore-forming materials (Xia Yong, 1991). In space, from north to south, the deformation and ore-forming environments both become shallow. All the above goes to reveal the control of tectonic environment on gold metallogenesis, and tectonic activities are the driving force for gold metallogenesis. Therefore, in metallogenic prognosis close attention should be paid to the characteristics of various structures (Bursnall, 1989). On the basis of the ore-controlling features in the shear zone, the ore-search orientation is described as follows: in the hanging-wall strata developed in the northern part of the Gezhen shear zone, attention should be paid to the search of the Bumo-type gold deposits in the relatively shallow ore-forming environment, while in the southern part attention should be paid to changes at depth in the shear zone and efforts should be devoted to the search of the Baoban-Tuwaishan- or Erjia altered mylonite-type gold deposits in the relatively deep strata. In the prognosis of gold deposits occurring in the Baoban Group source strata, attention also should be paid to the expanded locations during the formation of the Gezhen shear zone.

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