Geological Characteristics and Zircon U-Pb Dating of Volcanic Rocks from the Beizhan Iron Deposit in Western Tianshan Mountains, Xinjiang, NW China

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Abstract: The Beizhan large iron deposit located in the east part of the Awulele metallogenic belt in the western Tianshan Mountains is hosted in the Unit 2 of the Dahalajunshan Formation as lens, veinlets and stratoïd, and both of the hanging wall and footwall are quartz-monzonite; the dip is to the north with thick and high-grade ore bodies downwards. Ore minerals are mainly magnetite with minor sulfides, such as pyrite, pyrrhotite, chalcopyrite and sphalerite. Skarnification is widespread around the ore bodies, and garnet, diopside, wollastonite, actinolite, epidote, uralite, tourmaline, sericite and calcite are ubiquitous as gangues. Radiating outwards from the center of the ore body the deposit can be classified into skarn, calcite, serpenitine and marble zones. LA-ICP-MS zircon U-Pb dating of the rhyolite and dacite from the Dahalajunshan Formation indicates that they were formed at 301.3±0.8 Ma and 303.7±0.9 Ma, respectively, which might have been related to the continental arc magmatism during the late stage of subduction in the western Tianshan Mountains. Iron formation is genetically related with volcanic eruption during this interval. The Dahalajunshan Formation and the quartz-monzonite intrusion jointly control the distribution of ore bodies. Both ore textures and wall rock alteration indicate that the Beizhan iron deposit is probably skarn type.

Key words: iron ore, Zircon U-Pb dating, skarnization, Beizhan, Western Tianshan Mountains

1 Introduction

Recently, great progress has been achieved in iron exploration in the western Tianshan Mountains due to the discovery of several medium to large-size Fe deposits, which include Chagangnuoer, Beizhan, Zhibo (Nuoerhu), Dunde, and Songhu (Zhang Z. et al., 2011). The Beizhan iron deposit was first recognized in 1965 as an occurrence with a strong magnetic anomaly. Detailed exploration work has been carried out during 2004–2006 by the No. 11 Unit of the Bureau of Geology and Mineral Resources Development of Xinjiang, and they confirmed an ore reserve of 226 million tons. Up to now, the Beizhan iron deposit has only been poorly investigated. Guo et al. (2009) summarized the geological characteristics and ore prospecting criteria of the Beizhan deposit and concluded that the volcanic sediments and skarnization together contributed to the iron formation. However, geological features, geochemistry, geochronology, and the geodynamic background of the Beizhan iron deposit is still poorly understood. This study is based on detailed field investigation, thorough mineralogic study and dating of volcanic rocks, with the aim of elucidating ore-forming mechanisms and mineralization age. We also aim to offer useful information for summarizing Fe mineralization mechanisms and metallogenic regularity of the Awulate Fe belt.

2 Regional Geology

The western Tianshan Mountains are located in the northern part of west Xinjiang. They are generally wedge-
shaped to the east, and bounded by the Yilianhabierga fault (the North Tianshan Mountains suture zone) to the North, the Changawuzi–Wuwamen suture zone (the South Tianshan Mountains suture zone) to the South, extending to Kazakhstan in the west, and to Northeast Kumishi to the east (Fig. 1b). The western Tianshan Mountains have
undergone a complex tectonic evolution, including the Paleo- and Mesoproterozoic Pangea accretion and breakup, the Neoproterozoic Rodinia supercontinent formation and breakup (Zuo et al., 2008), the Meso- to Neoproterozoic crystalline basement formation (Gao et al., 1995; Qian et al., 2006; Li et al., 2009), and the Paleozoic multiplate (microplate) and multi-island-arc paleo-Asian ocean evolution (Zuo et al., 2008). The western Tianshan Mountains have also experienced south- and north-direction collision accretion events (Allen et al., 1992), and an accretion orogenesis event that possibly ended at the late stage of the Early Carboniferous. And the collision between Karakum-Tarim and Kazakhstan-Junggar plates, probably took place during the late Carboniferous in the southwestern Tianshan Mountains (Kang et al., 2011). From the western Tianshan Mountains to central Asia evolved to a post-collision stage during the Permian and belongs to a Neoproterozoic orogenic belt (Gao et al., 2009).

The Chagangnuoer-Beizhan Fe ore cluster at the east part of the western Tianshan is tectonically located at the Yili Carboniferous-Permian rift (Fig. 1b). The region exposes Archean, Silurian, Devonian, Carboniferous, Permian, Triassic, Jurassic and Quaternary in ascending order. Among them the Carboniferous Dahalajunshan Formation is dominant. The Dahalajunshan Formation consists of thick widespread volcanic rocks with complex lithology and lithofacies. Sedimentary paleoenvironment and tectonic setting of the Dahalajunshan Formation are still controversial, which has been suggest as eruption rocks in continental rift (Che et al., 1996; Yang et al., 2003) and large igneous province related mantle plume (Xia et al., 2002). With respect to the tectonic setting, interpretations including Carboniferous oceanic arc alkaline volcanic rock formation (trench-arc-basin system) (Jiang et al., 1995), typical continental volcanic arc environment (Zhu et al., 2005, 2006a, 2009), passive continental margin back arc extension environment (Qian et al., 2006; Li et al., 2010), and continental margin arc environment (Li et al., 2006; Long et al., 2008; Li et al., 2009) are popular.

The Chagangnuoer-Beizhan ore cluster (Fig. 1c) consists of four medium-large size iron deposits, including Chagangnuoer, Zhibo, Dunde and Beizhan Fe deposits. Except for Fe deposits, this region also occurs many Cu deposits with variable reserves.

### 3 Ore Deposit Geology

Generally, strata in the mining area occur in a syncline, mainly consisting of the Carboniferous Dahalajunshan Formation overlain by the Quaternary. The Dahalajunshan Formation is exposed in the central mining area for about 7.5 km² with a thickness of 717.74 m (Fig. 2) and can be classified into three geological units according to lithology and metamorphic degree. Unit 1 in the Beizhan Fe deposit consists of tuff with andesite in the northern part, and tuff with tuffaceous conglomerate to the south. Unit 2 is exposed in the north of the mining area and around ore bodies and mainly consists of gray banded limestone, thinly bedded limestone, dolomite limestone, dolomite, and local marble. Unit 3 is exposed in the central mining area; the lower part is dark gray rhyolite succeeded gradually by calcic shales, carboniferous shales or mud with a dolomite interlayer and thinly bedded limestone upwards. The mining area is located at the north of the regional Xigezidaban syncline, which is composed by the Carboniferous Dahalajunshan Formation Unit 3 at its axis with Units 2 and 1 as wings. Faults are developed in the mining area, nine (mostly high-angle compresso-shearing normal faults) of which are important. Magmatic rocks in the area consist of quartz-monzonite porphyry (locally quartz-syenite porphyry), granite porphyry, diorite and diabase dykes.

A total of six ore bodies (L1–L6) hosted in the Dahalajunshan Formation Unit 2 have been identified, and among them L3 is the most economically important. The L3 is a 630 m-long EW-trending lens-vein-stratiform ore body with an average dip angle of 37–39° to the north more
than 380 m (steeper upwards) (Fig. 3a). It is 5–139 m thick (62 m on average) with an average grade of total Fe varying from 23.0 to 64.3 wt.% (41.0 wt.% on average). The ore body becomes thicker downwards with a higher grade of Fe. The wall rock of quartz-monzonite porphyry exhibits strong skarnization alteration.

The dominant ore mineral is magnetite. Small amounts of pyrite, pyrrhotite, chalcopyrite, sphalerite are intergrown with the magnetite. Gangue minerals are mainly skarn, including garnet, diopside, wollastonite, actinolite, epidote, uralite, tourmaline, sericite and calcite.

The ore occurs as massive, breccia, disseminated and veinlet. The massive ore is the main type with high ore grade (over 50 wt.% Fe). Magnetite in the massive ore occurs as anhedral–subhedral grain. Minor pyrite and pyrrhotite can be observed (Fig. 3b). Gangue minerals (e.g. calcite) are scarce in the massive ore. Brecciated ore consists of diopside, epidote, actinolite and garnet; grainsize is variable, ranging from 5 mm to 2 cm (Fig. 3c, e). Magnetite in the breccia-type ore occurs as cement with variable contents. Magnetite content in the disseminated ore is relatively low, with Fe grade of 20 to 35 wt.%, occurring as a thin layer. Veinlet-type ore is minor, with magnetite occurring as veins and banded with chlorite and epidote alteration (Fig. 3d). Skarnization is widespread in the ore bodies. Garnet, hedenbergite and wollastonite are commonly distributed as banded skarn (Fig. 3f).

Textures of the iron ore include filling architecture, metasomatic replacement and subhedral–anhedral grains (Fig. 3g, h, k). Fine-grained pyrrhotite intergrown with euhedral pyrite can occasionally be observed (Fig. 3i). Microscope observation indicates that widespread dark green euhedral hedenbergite is commonly surrounded by actinolite. Magnetite in tiffs fracture or interacts with actinolite, showing metasomatic relict texture (Fig. 3h, j). Wollastonite occurs as lamellar, acicular and fiboid crystals seen under the microscope with gray-white or gray-yellow interference colors (Fig. 3i).

Wall rock alteration is widespread in the mining area. From the center of the ore body outwards skarn, calcite, serpentinite and marble zones can be identified. Skarn occurs mainly around ore bodies, comprising diopside and epidote, with minor uralite, wollastonite, garnet, actinolite and tourmaline. Although there is no sharp boundary of skarn zonation, epidote–diopside, uralite–wollastonite–garnet, and actinolite–tourmaline skarn zones can still be generally identified from the center outwards. Calcite alteration occurs around the ore body margin as irregular veins, indicating that the calcite occurred after the mineralization stage and has no obvious genetic relation with the Fe mineralization. Serpentinite occurs as a yellow-green wax-like thin shell, aggregates and fibroid. The serpentinite alteration normally occurs along fractures and cleavages, and locally contains high-grade magnetite. Marble occurs along the contact zone and beyond ore bodies. Widespread marble occurrences, usually accompanied by an ore body thin out.

4 Zircon LA-ICP-MS U-Pb Dating

4.1 Features of volcanics

In order to know the tectonic background of the Beizhan Fe mineralization, this study collected the volcanic rocks exposed in the mining area for LA-ICP-MS zircon U-Pb dating. The lithology of the samples can be described as follows:

Rhyolite: hand specimen is purple-red in color with porphyritic texture; phenocrysts include plagioclase and quartz. The plagioclase (10–15 vol.%) occurs individually or grouped as white euhedral–subhedral sheets. Fissures and multiple twins are common. The size of the plagioclase phenocrysts varies from 0.5 to 3 mm. Quartz crystals (3–5 vol.%) are 0.5 to 1 mm in size, colorless, anhedral, and fragmented (Fig. 4a). Except for fragments of feldspar and quartz in the matrix, sericite is widespread (80–85 vol.%).

Dacite: plagioclase and quartz are the two predominant phenocrysts within gray-white porphyritic calcite. The plagioclase (10–15 vol.%) occurs as white, euhedral–subhedral sheets and columns of 1 to 5 mm in size, and is commonly altered by epidote and chlorite. Mutiple twin is common. The quartz (10–15 vol.%) is colorless, anhedral, bay-like (concave) and serrated with crystals of variable size of 0.5 to 3 mm (Fig. 4b). The sample had undergone weak epidote and chlorite alteration. The matrix consists of quartz, feldspar and chlorite with poikilitic texture.

4.2 Analytical method

U-Pb dating analyses were conducted on the LA-MC-ICP-MS at the Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing. Detailed analytical procedures and operating conditions for the laser ablation system are described by Hou et al. (2009). Laser sampling was performed using a Newwave UP 213 laser ablation system. A Thermo Finnigan Neptune MC-ICP-MS instrument was used to acquire ion-signal intensities. The array of four multi-ion-counters and three Faraday cups allow for simultaneously detection of $^{206}$Hg (on IC5), $^{204}$Hg, $^{206}$Pb (on IC4), $^{208}$Pb (on IC3), $^{206}$Pb (on IC2), $^{208}$Pb (on L4), $^{232}$Th (on H2), and $^{238}$U (on H4) ion signals. Helium was applied as a carrier gas. Argon was used as the make-up gas and mixed with the carrier gas via a T-connector before entering the ICP. Each analysis incorporated a background acquisition of approximately 20–30 s (gas blank) followed by 30 s data acquisition from the sample. Off-line raw data
Fig. 3. Ore features of the Beizhan iron deposit.

a, overview of the Beizhan Fe deposit; b, massive ore; c, brecciated ore; d, banded ore; e, magnetite replacing garnet; f, skarn zonation; g, magnetites infilling fissures between heedenbergite and actinolite, (transmitted light); h, magnetite replacing actinolite (crossed polar light); i, tabular and acicular wollastonite (crossed polar light); j, actinolite relics in magnetite (reflected light); k, euhedral granular magnetite (reflected light); l, anhedral disseminated magnetites and euhedral pyrite (reflected light). Mag, magnetite; Py, pyrite; Grt, garnet; Act, actinolite; Px, pyroxene; Wo, wollastonite; Ep, epidote; Chl, chlorite; Cal, calcite.

Fig. 4. Photomicrographic features of (a) rhyolite and (b) dacite from the Beizhan iron deposit, western Tianshan Mountains.

Ab, albite; Qtz, quartz.
selection and integration of background and analyte signals, time-drift correction and quantitative calibration for U-Pb dating were performed by ICPMSDataCal (Liu et al., 2010).

Zircon GJ1 was used as an external standard for U-Pb dating, and was analyzed twice every 5–10 analyses. Time-dependent drifts of U-Th-Pb isotopic ratios were corrected using a linear interpolation (with time) for every 5–10 analyses according to the variations of GJ1 (i.e., 2 zircon GJ1 +5 samples + 2 zircon GJ1) (Liu et al., 2010). Preferred U-Th-Pb isotopic ratios used for GJ1 are from Jackson et al. (2004). Uncertainty of preferred values for the external standard GJ1 was propagated to the ultimate results of the samples. The usual Pb correction was not necessary in all analyzed zircon grains because of the low signal of common $^{204}$Pb and high $^{206}$Pb/$^{204}$Pb. U, Th and the Pb concentration was calibrated by zircon M127 (with U: 923 ppm; Th: 439 ppm; Th/U: 0.475. Nasdala et al., 2008). Concordia diagrams and weighted mean calculations were made using Isoplot/Ex_ver3. The zircon Plesovice is dated as unknown samples and yielded weighted mean $^{206}$Pb/$^{238}$U age of 336.7±0.95 Ma ($\tau$=14, 2$\sigma$), which is in good agreement with the recommended $^{206}$Pb/$^{238}$U age of 337.13±0.37 Ma (2 SD) (Sláma et al., 2008).

4.3 Analytical results

Zircons from rhyolite sample BZ2 are 100–150 µm in size, and mainly euhedral with a small amount of short columnar-shaped grains. Cathodoluminescence (CL) images of zircons show clear oscillatory growth zonation (Fig. 5a). Th/U ratios of 18 zircons vary from 0.63 to 1.18 (Table 1), indicating that they are of magmatic origin (Rubatto, 2002). U and Th contents change from 104 to 521 ppm, and from 65 to 497 ppm, respectively. Zircon $^{206}$Pb/$^{238}$U ages vary from 301.8±1.8 to 306.0±1.5 Ma with a weighted average age of 303.7±0.9 Ma (MSWD=0.55) (Fig. 6a), representing the diagenetic age of the rhyolite.

The dacite sample BZ101 has similar characteristics to the rhyolite, such as 100–150 µm in size, euhedral or short columnar in shape, and oscillatory growth zonation observed in CL images (Fig. 5b). A total of 15 analyses are relatively concentrated (Table 1), with U, Th contents and Th/U ratios varying from 78 to 274 ppm, 96 to 281 ppm, and 0.67 to 1.36, respectively, also indicating that they are of magmatic origin (Rubatto, 2002). The $^{206}$Pb/$^{238}$U ages of

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Fig. 5. Cathodoluminescence (CL) images of zircons from the (a) rhyolite and (b) dacite from the Beizhan iron deposits, western Tianshan Mountains (circle indicates analyzing location; $^{206}$Pb/$^{238}$U ages (Ma) are applied and corresponding data are listed in Table 1).
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**Table 1 LA-ICP-MS U-Pb isotopic analyses for zircons from the rhyolite (BZ2) and dacite (BZ101) from the Beizhan iron deposits, western Tianshan Mountains**
these zircons vary from 299.5 ± 1.0 to 304.0 ± 1.4 Ma, and the weighted average age is 301.3 ± 0.8 Ma (MSWD = 1.08), indicating that the diagenetic age of the dacite was similar to that of the rhyolite. Three zircons obtained gave inconsistent dates of 322.6 ± 5.4 Ma, 325.1 ± 1.6 Ma and 350.8 ± 1.1 Ma (Fig. 6b), possibly reflecting that they were captured during an eruption.

5 Discussion

5.1 Geodynamic setting

The Dahalajunshan Formation volcanic rocks are widely exposed in the western Tianshan Mountains and exhibit variable ages (spanning ~50 Ma). The age of the volcanic rocks becomes younger from west to east, with Late Devonian (~363 Ma) volcanic rocks in the Gonglu–Tekesi area (western part of the mountains), Early Carboniferous (~354 Ma) volcanic rocks in the north part of the Nalati area at the southern margin of Xinyuan County (central part of the mountains), and Late Carboniferous (~313 Ma) volcanic rocks in the Laerdudaban area (east part of the mountains) (Zhu et al., 2005, 2006b, 2009; Zhai et al., 2006; An and Zhu, 2008). In recent years, the Awulale iron metallogenic belt has been identified due to many iron deposits related with Carboniferous Dahalajunshan Formation volcanic rocks that were discovered in the east part of the western Tianshan Mountains (Feng et al., 2011). To know the accurate age of the volcanic rock is therefore significant to better understand the geodynamic background of iron formation. LA-ICP-MS zircon U-Pb dating indicates that the formation ages of the rhyolite and dacite in the Beizhan iron deposit were 301.3 ± 0.8 Ma and 303.7 ± 0.9 Ma, respectively, which is strictly consistent with the age of volcanic rocks from the Chagangnuoer and the Zhibo iron deposits (300–305 Ma, unpublished date) within the same metallogenic belt. Similar ages of volcanic rocks indicate that the hosted iron deposits were formed under a uniform geodynamic event. The ages of the volcanic rocks yielded in this study are relatively younger than the previously reported ages of the Dahalajunshan Formation, suggesting that the age of the Dahalajunshan Formation is variable at the regional scale, which may be the result of polycyclic volcanic event.

As mentioned above, there are several interpretations with respect to the forming environment of the Dahalajunshan Formation volcanic rocks. The most popular interpretation is that they are calc-alkaline volcanic rocks and formed under continental margin or oceanic arc environments (e.g., Zhu et al., 2005; Guo and Zhu, 2006; Wang et al., 2007; Li et al., 2006; Long et al., 2008). Except for the widespread calc-alkaline volcanic rocks, small amounts of Late Carboniferous high-K volcanic rocks and intrusive rocks are also exposed locally (Zhu et al., 2006a; Luo et al., 2009; Zhu et al., 2011). Geochemistry data of the volcanic rocks from the Chagangnuoer and the Zhibo iron deposits suggest that they are high-K calc-alkaline type, possibly corresponding to the late stage of subduction (Wang et al., 2011). Zhang X. et al. (2011) reported A-type granites with post-collisional features in the Zhibo iron deposit, and their work yielded two dates of 304.1 ± 1.8 Ma and 294.5 ± 1.6 Ma, indicating that this region might have undergone a tectonic transformation from a collisional orogenesis stage to post-collisional extension during 304 to 295 Ma.

Regional study indicates that the accretionary processes of the western Tianshan Mountains may be related with the coalescence and closure of the Early Paleozoic Tienersikei paleocean, the Late stage of the Early Paleozoic to Late
Paleozoic Southern Tianshan Mountains ocean, and the Late Paleozoic Northern Tianshan Mountains ocean, an accretionary orogenesis event that might have ended around the Late Carboniferous (>300 Ma) (Gao et al., 2009). During the Late Carboniferous to Early Permian (300 to 260 Ma), the tectonic background at the western Tianshan Mountains was transformed from subductive and orogenic compressive stress to post-collisional extension (Zhao et al., 2003, 2008), followed by an intracontinental rift-type eruption, which are characterized by widespread bimodal volcanic rocks (Gao et al., 2009). In summary, combined with the regional geological data, the volcanic rocks exposed in the Beizhan iron deposit are 301.3±0.8 Ma and 303.7±0.9 Ma, respectively, which may be related to the continental arc magmatism during the late stage of subduction in the western Tianshan Mountains.

5.2 Iron mineralization

The Carboniferous Dahalajunshan Formation is ubiquitous in the mining area. Ore bodies are mainly hosted in the gray-banded limestone and dolomite of Unit 2 of the Dahalajunshan Formation, indicating that it is genetically related with iron formation. On the other hand, the quartzmonzonite is intruded into the Dahalajunshan Formation, relics of which still can be found locally in the intrusion (Fig. 2). Only small amounts of ore bodies occur at the contact zone, where skarn minerals such as garnet, diopside, wollastonite, actinolite, epidote, uralite, tourmaline, sericite and calcite are common. Spatially, the overlain and underlain wall rock of the ore bodies are quartz-monzonite, and these strongly indicate that the intrusion has contributed to the skarnization and iron formation. In summary, the Dahalajunshan Formation volcanic rocks and quartzmonzonite jointly controlled the distribution of ore bodies, and both of them offered metals and hydrothermal fluids.

Magnetite occurs as massive, breccia, disseminated and veinlet with filling, replacement, subhedral-anhedral grain textures. Skarnization is the most significant feature of the Beizhan iron deposit, which commonly occurs as garnet, diopside, wollastonite, actinolite, epidote, uralite, tourmaline, sericite and calcite. From the center of the ore body outdoors to wall rocks, skarn-, calcite-, serpentinite-, and marble-zone have been identified. In detail, the skarn zone can be further classified into chlorite-diopside skarn, uralite-wollastonite-garnet skarn, and actinolite-tourmaline skarn zone. Ore minerals including large amounts of magnetite and minor sulfides such as pyrite and pyrrhotite are intergrown with skarn minerals. Mineral paragenetic study indicates that high-temperature minerals such as garnet, pyroxene, actinolite, wollastonite formed at an early stage. Garnet and pyroxene of this stage are characterized by large and relatively euhedral grains. Magnetite is precipitated at the intermediate stage and is commonly infilled or replaced by skarn minerals such as pyroxene and actinolite. Calcite and serpentinite are generally formed at the hydrothermal alteration stage (late stage) after iron formation. Overall, the Beizhan iron deposit is not only characterized by typical skarn zonation, but have generally similar mineral assemblages with other skarn iron deposits. All these features indicate that the Beizhan iron deposit is the skarn type with ore bodies predominating in the endoskarn (Einaudi and Burt, 1982; Meinert et al., 2005). This skarn belongs to calcite skarn, which is apparently different from the magnesian skarn mentioned by Zhao et al. (1998).

The simplified mineralization processes of the Beizhan iron deposits can be classified into two stages: (1) during the Late Carboniferous, large amounts of volcanic rocks including andesite, andesitic tuff, trachyandesite, rhyolite and dacite erupted and formed the Dahalajunshan Formation. Locally precipitated limestone, dolomite and mudstone during this interval offered an ideal factory for iron formation; (2) subsequently, the Dahalajunshan Formation Unit 2 of calcium-bearing carbonates were intruded by the quartz-monzonite porphyry, which carried copious hydrothermal fluids. The intrusion interacted with the limestone and dolomite, resulting in metals that were leached out from the Fe-bearing andesitic strata. High-temperature minerals such as garnet, pyroxene and wollastonite formed at the early stage, followed by actinolite, magnetite, epidote, sulfides, sericite and calcite formation with temperature decreases and mixture with meteoric water. The lens-veinlet-stratiform ore bodies and skarn zonation formed during this stage.

6 Conclusions

(1) LA-ICP-MS zircon U-Pb ages of the Dahalajunshan Formation rhyolite and dacite from the Beizhan iron deposit are 301.3±0.8 Ma and 303.7±0.9 Ma, respectively, which might be related with continental arc magmatism during the late stage of subduction in the western Tianshan Mountains. Iron formation is genetically related with the volcanic eruption during this interval.

(2) The Dahalajunshan Formation in combination with quartz-monzonite controlled the distribution of the iron mineralization. Ore fabrics and textures show typical features of a skarn iron deposit. The volcanic rock formation offered the necessary condition for iron mineralization, whereas the subsequent quartz-monzonite intrusion finally led to skarnization and Fe precipitation.

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