Gem-Grade Garnet With Metamorphic Origin in the Tiemurt Orogenic-Type Deposit, Chinese Altay Orogen: Texture, Chemistry, and Physicochemical Condition

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The Chinese Altay Orogen represents an accretionary collage with episodic subduction-related accretion from the Neoproterozoic to Permian, followed by Triassic continent–continent collision. Reddish gem-grade garnet grains are widespread in Au–Cu–Pb–Zn sulfide deposits of the Chinese Altay Orogen, and how their formation links to regional geological processes such as seafloor sedimentation, magmatic hydrothermal metasomatic, or orogenic metamorphism remains unclear. In this context, we present an integrated set of geological occurrences, mineral texture, and major trace elemental geochemistry of six garnet grains from the representative Tiemurt Cu–Pb–Zn(-Au) deposit. Two categories of garnets, Grt1 and Grt2, are identified in terms of distinct mineral assemblages, textures, and geochemistry. The sub- to euhedral biotite inclusion–rich Grt1 with fine grains of less than 0.3 cm in diameter is intergrown with amphibole, chlorite, and biotite. Comparatively, the euhedral mineral inclusion–poor Grt2 with coarse grains of 0.5–5 cm in diameter is paragenetic with quartz, calcite, chlorite, and biotite. Forty-one EMPA analyses show that Grt1 and Grt2 have similar major elemental compositions of SiO2 (36.2–37.5 wt%), Al2O3 (19.9–20.7 wt%), and CaO (5.3–7.8 wt%) but host variable contents of FeO (31.7–35.9 wt% for Grt1 and 23.0–30.0 wt% for Grt2) and MnO (0.8–3.7 wt% for Grt1 and 4.3–12.7 wt% for Grt2). Both Grt1 (with a chemical formula of Alm49.3–54.6Spe19.7–24.6Gro14.6–18.4Pyr3.7–4.8And3.5–4.9) and Grt2 (Alm57.4–64.4Gro15.5–18.3Spe9.6–19.8Pyr3.8–5.7And1.1–4.4) are plotted into the field close to the end-member of almandine (Fe-Al–garnet). Compared to Grt1, Grt2 displays a Fe-enriched and Mn-depleted trend. Additionally, Mn is enriched in the core but Fe is enriched in the rim on the major elemental profile of Grt1. Regarding the trends of trace elements and REEs, Grt2 is believed to be produced during the detriment and replacement of Grt1 by an intense external metal-rich fluid. In combination with previous fluid inclusion research, the garnet-related fluids are characterized by CO2-rich, mesothermal, mildly acidic, and reduced redox, analogous to metamorphic fluids generated during orogenesis. Collectively, we conclude that the reddish gem-grade garnet crystals in the Chinese Altay Orogen are of metamorphic origin.

Keywords: garnet, metamorphic origin, orogenic-type deposit, Tiemurt Pb–Zn–Cu deposit, Chinese Altay Orogen
INTRODUCTION

Garnet is a widespread silicate mineral in variable geological settings on Earth, for example, mantle transition zone, subducting ocean crust, skarn deposits with magmatic hydrothermal origin, seafloor sedimentary exhalation, and metamorphic rocks (Marco and Donald, 1982; Doyle and Allen, 2003; Meineit et al., 2005). Different garnets host a similar crystal structure of \([	ext{SiO}_4]\) tetrahedrons with the chemical formula of \(\text{Al}_2\text{B}_2(\text{SiO}_4)_3\), in which \(A = \text{Ca}^{2+}, \text{Fe}^{2+}, \text{Mg}^{2+}\), and/or \(\text{Mn}^{2+}\), while \(B = \text{Al}^{3+}, \text{Fe}^{3+}, \text{and/or} \text{Cr}^{3+}\) (Menzer, 1926; Bernard et al., 2013; Dietrich, 2020). Two principal categories of garnets with different chemical compositions have been well documented, that is, the Al-rich garnet (represented by pyrope, almandine, and spessartine) and Fe-rich garnet (grossular, uvarovite, and andradite) (Charles, 2016). In particular, the chemical variations of these garnets, coupled with mineral growth zonation, are often used as a sensitive indicator of physicochemical conditions, such as pressure (\(P\)), temperature (\(T\)), redox state, and acidity (Jamtveit et al., 1993; Konrad-Schmolke et al., 2005; Baxter and Scherer, 2013). Linkage of garnet mineral growth and metal accumulation has received much attention in the skarn deposits (Jamtveit et al., 1993), owing to the substantial Ca-rich garnet produced by contact replacement of magmatic fluids with host carbonates (Xu et al., 2016; Park et al., 2019). However, garnet geological indicator is rarely used in other genetic-type metal deposits largely because of its scarcity.

An abundance of reddish gem-grade garnet has been discovered in the Au–Cu–Pb–Zn polymetallic ore deposits in the Chinese Altay Orogen, but their origin remains unclear (Chen, 2000; Yang et al., 2018). In fact, ore genesis of these polymetallic ore deposits is also intensively debated as the volcanicogenetic massive sulfide (VMS), metamorphosed VMS, or orogeny-driven metamorphic hydrothermal (orogenic-type) deposits (Zheng et al., 2013b; Stefanie et al., 2014). These controversies are partially due to most of these polymetallic deposits possessing significant characteristics of textural modification and chemical remobilization during the subsequently magmatic and metamorphic overprinting (Jamtveit et al., 1993; Giobanu and Cook, 2004; Barrie et al., 2010). It is hard to evaluate the contribution of seafloor sedimentation or subsequent orogenesis for these polymetallic deposits in the Chinese Altay Orogen (Yu and Zheng, 2019). Therefore, these garnet grains have great potential to answer the questions of how the metals were enriched up to ores.

The representative Tiemurt Pb–Zn–(Cu–Au) deposit hosts large amounts of garnet grains paragenetic with the chief sulfide ores (Zheng et al., 2013a; Zhang et al., 2017a; Yu and Zheng, 2019). To address the above scientific issue, we conducted an integrated set of paragenetic sequence, internal textures, and their corresponding in situ major and minor elemental compositions of the Tiemurt garnet. The growth history and physicochemical condition of garnet is believed to assist to yield much clearer understanding on the ore genesis and regional metallogeny (Konrad-Schmolke et al., 2005). In addition, this research might shed light on the reconstruction of tectonic evolution of the Chinese Altay Orogen and even CAOB.

GEOLOGICAL BACKGROUND

Tectonic Settings

The Central Asian Orogenic Belt (CAOB), the largest accretionary orogen on Earth (Jahn, 2004; Xiao et al., 2009; Chen et al., 2012), is located between the Siberia Craton to the north and Tarim–Sinokorea Craton to the south (Figure 1A). An abundance of Paleozoic ophiolites, arc igneous rocks, and Precambrian masses records a complex accretionary history prior to the Triassic collisions of the Siberian with Tarim–Sinokorea Craton (Xiao et al., 2009).

As an important element of CAOB, the Chinese Altay Orogen is an accretionary complexity toward the southern margin of the Siberian Craton and contains four principle tectonic units from north to south (Figure 1B; Chen et al., 2012), including 1) Unit 1: the Late Devonian–Early Carboniferous Nurt volcanic basin developed on aPrecambrian crystalline basement; 2) Unit 2: the Paleozoic Keketuohai magmatic arc that contains Precambrian high-grade metamorphic rocks, Neoproterozoic–Earliest Triassic granites, and the giant Keketuohai pegmatite field; 3) Unit 3: the Devonian–Carboniferous volcanic basins developed on the southern margin of the pre-Devonian metamorphic rocks, for example, the Kelan, Ashele, and Maizi basins; and 4) Unit 4: the Armanuy–Ertix accretionary terrane and Devonian–Carboniferous fossiliferous sedimentary rocks, intruded by post-orogenic granites.

The basins in Unit 3 of the Chinese Altay Orogen is filled by a package of low-grade metamorphosed volcano-sedimentary rocks comprising the continentally derived turbidites (e.g., Habahoe Group), volcanic rocks (e.g., Altay Formation), and volcanic-sedimentary rocks (e.g., Kangbutiebao Formation) (Wang et al., 1998; Goldfarb et al., 2003). It is notable that these basins are metal-fertile and hosting considerable amount of metal deposits. The representative deposits include the giant Ashele Cu–Zn, Keketale Pb–Zn, Mengku Fe deposits (Wang et al., 1998; Wan et al., 2010a, 2010b; Zheng et al., 2013b), and numerous polymetallic lode deposits (Figure 2A; e.g., the Sarekuobu Au, the Wulasigou Cu deposit, and Tiemurt Au–Cu–Pb–Zn deposits (Zhang et al., 2012; Zheng et al., 2012; Yu et al., 2020).

Field Geology of the Kelan Basin

The Kelan Basin is particularly rich in the Au–Cu–Pb–Zn lode deposits that are controlled by a series of complex structures. A huge multiple overturned syncline system, with the axial plane dipping toward northwest, is identified in the Kelan Basin (Figure 2A). The well-developed NW-trending faults are the chief ore-controlled structures and also separate the distinct stratigraphic units, that is, the Keyingong and Hongdun faults separate the Kulumiti Group and the Kangbutiebao Formation, while the Abagong and Altay faults separate the Kangbutiebao and Altay Formations (Figure 2A).

Among the strata, the Silurian Kulumiti Group with lithological composition of migmatite, gneiss, and schist is unconformably overlain by the Devonian Kangbutiebao and Altay formations. The Kangbutiebao Formation consists of a set of felsic lavas, pyroclastic rocks, and siliciclastic
FIGURE 1 | (A) Tectonic framework of the Central Asian Orogenic Belt. (B) Geological sketch map showing the tectonic units of North Xinjiang (Chen et al., 2012). Siberia plate: S1, Late Devonian–Early Carboniferous Nurt volcanic basin; S2, Paleozoic Keketuohai magmatic arc; S3, Devonian–Carboniferous Kelan forearc basin; S4, Armantay-Irtysch accretionary wedge. Kazakhstan plate: K1a, Zharma-Sawur island arc; K1b, Western Junggar accretionary complex; K1c, Eastern Junggar accretionary complex; K1d, Mesozoic–Cenozoic Junggar basin; K1e, Late Paleozoic Yelihanhabirga backarc basin; K1f, Late Paleozoic Bogada aulacogen; K1g, Paleozoic Harlike island arc; K1h, Daranhu island arc; K1i, Mesozoic–Cenozoic Turpan basin; K2a, Salimu massif; K2b, Wenzhou terrane; K2c, Paleozoic Boloholo arc basin system; K2d, Paleozoic Yamanus-Jueluqot arc basin system; K2e, Carboniferous–Permian Lii rift; K2f, Early Paleozoic central Tianshan island arc with Precambrian fragments; K2g, NaLai massif. Tarim Plate: T1, Mesozoic–Cenozoic Tarim basin; T2a, Precambrian Kurnuktag massif; T2b, Muzart massif; T3a, Carboniferous–Permian Beishan aulacogen; T3b, Late Paleozoic Kalatierek passive marginal sediments; T4a, Late Paleozoic Southwest Tianshan fold-thrust belt; T4b, Paleozoic Southern Tianshan (or Kumishi) accretionary complex.

FIGURE 2 | (A) Geological map of the Kelan Basin and ore deposits, and the inserted geological map of the Tiemurt Pb–Zn–Cu deposit (modified after Geological Team 706 of the Xinjiang Bureau of Nonferrous Metals, 2000). (B) Geological cross sections of the Tiemurt ore bodies No. 4 and No. 27 (modified after Xinjiang Geological Team 706, 2000).
interlayered with marine carbonates with an eruptive age of \( \sim 400 \) Ma through zircon U–Pb dating (Chai et al., 2009; Zheng et al., 2015). Slate, greywacke, schist, and phyllite are the diagnostic rocks assemblage of the Altay Formation. In addition, all the abovementioned strata suffered regional amphibolite to greenschist-facies metamorphism during the subsequent Permian to Triassic orogenesis (Zhuang, 1994; Laurent et al., 2002). Limited Orodovician–Early Jurassic intermediate to felsic intrusions are exposed in the Kelan Basin (Figure 2A).

**Ore Deposit Geology of the Tiemurt**

The Tiemurt polymetallic deposit contains a confirmed metal reserve of Pb–Zn (0.29 million tons) and Cu (0.15 million tons), as well as economic Au (8 tons). Three principal lode ore bodies (Nos. 1, 4, and 27) accounted for \( \sim 90\% \) of the total reserves. They are controlled by the Abagong Fault and its subordinate faults that trend to NW trending with a highly dipping angle of 49–80° (Figure 2B). Intensive alterations, marked by quartz, calcite, chlorite, epidote, biotite, amphibole, tremolite, and garnet, are widely presented along the ore bodies and ore-controlled faults in the ore-hosting Kangbutiebao Formation.

A majority of metallic minerals, including pyrite, galena, sphalerite, chalcopyrite, and pyrrhotite, present ore fabrics of massive, banded, disseminated, or as veinlets and breccias. Taking into account of paragenesis sequences, two major metallogenic ore-forming stages attributed to metal accumulation are identified, that is, the seafloor sedimentation and regional orogeny-related metamorphic hydrothermal activities (Yu and Zheng, 2019).

**SAMPLING AND ANALYTICAL METHODOLOGY**

**Sampling**

A total of six host rock samples that contain visible garnet grains were collected from the Nos. 4 and 27 ore bodies at Tiemurt. These samples can be categorized into two types of sulfide-bearing (mineralized) and -barren (unmineralized) ones, respectively (Figure 3). All samples were polished into thin sections with thickness of 30 μm for petrographic study (Figure 4). After petrographic examination under microscope, three samples (Nos. 10TMZK-49, 10TM-26-1, and 10TM-26-2) were conducted for textural and mineral chemical analyses. Six garnet grains and their paragenetic amphibole and biotite were analyzed to yield their textural characteristics by scanning electron microscope (SEM), as well as \( \text{in situ} \) major and trace elemental compositions using the coupled electron probe microanalysis (EPMA) and laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS), respectively. \( \text{In situ} \) LA-ICPMS and EPMA measurements were made at the same area of the minerals.

**Internal Textual Analysis by SEM**

After the detailed petrographic observation, we use a ΣIGMA scanning electron microscope (SEM) equipped with an X-MAX020 energy-dispersive spectrometer (EDS) that is housed at the School of the Earth Science and Geological Engineering, Sun Yat-Sen University (SYSU), to obtain internal textual information of the representative garnet grains. The instrument was operated on a backscattered electron (BSE) mode with an acceleration voltage of 20 kV, a beam current of 20 nA, and a beam diameter of less than 1 μm.

**Major Elements Analysis by EMPA**

To yield major element compositions of the six garnet grains and their paragenetic amphibole, we adopted the JXA-8800 R electron probe micro analyzer (EMPA) at SYSU and the JEOL JXA-8100 EPMA at the Guangzhou Institute of Geochemistry, Chinese Academy of Science (GIG, CAS). The similar working conditions were set at an acceleration voltage of 15 kV, a beam current of 20 nA beam, and a beam diameter of 1–2 μm. Each point analysis of major elements contains a 10–20 s background acquisition (gas blank) followed by a 20 s data acquisition of the sample.

**Trace Elements Analysis by LA-ICP-MS**

To acquire the \( \text{in situ} \) minor and trace elemental compositions of garnet grains coupled with the above textures and major
elements, we operated a laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the GIG, CAS. Each ablative spot of garnet grain was performed at the size of \(47 \mu m\) in diameter, the laser repetition rate of 5 HZ, and the beam energy of \(\sim 7.2 \text{ J/cm}^2\) using helium as the carrier gas. The operation time include a 30 s background and a 60 s elemental information measurement. Thirty-five elements (Sc, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, Pb, Th, and U) were measured. Data quantification is used in the united method of the internal standard method (Longerich et al., 1996) and the external standard of zircon 91,500 (Wiedenbeck et al., 1995). To monitor the instrumental drift, we analyzed the standard twice every 1.5 h at the condition of a 100 \(\mu m\) beam and a 10 Hz laser repetition rate.

RESULTS

Textural Characteristics of Garnet Grains
As illustrated in the Table 1 and Figure 3, the garnet grains are commonly intergrown with amphibolite, biotite, chlorite, calcite, chalcopyrite, pyrite, and sphalerite. Most of garnet grains present euhedral to subhedral crystals with a diameter of 0.3–5 cm in diameter (Figure 3A). In combination with their reddish color and good transparency, they can be classified into the gem-grade garnet (Figure 4). No distinctive textural zonation was observed in these garnet grains in microscopic observation and in BSE imaging (Figures 3C–F, 4, 5).

A slight difference is identified between these garnet grain samples. The garnet grains in samples 10TM-26-1 and 10TM-26-2 are intergrown with calcite, biotite, chalcopyrite, and chlorite with a smaller grain size of 0.01–3 cm in diameter (Figures 4A–D). In contrast, the garnet grains in sample 10TMZK-49 coexist with chlorite, amphibole, and biotite with a diameter of 0.5–5 cm in diameter (Figures 4E–H).

Major Elemental Compositions
The Supplementary Table S1 shows all the major elemental compositions of 41 spots in six representative garnet grains from three samples, and the Table 2 presents the selected major elements with relatively high contents.

Garnet
A total of 41 EMPA spot analyses were completed on the six garnet grains, including 13 spots on sample 10TMZK-49 and 14 spots each for samples 10TM-26-1 and 10TM-26-2. The results indicate that garnets in 10TMZK-49 have SiO<sub>2</sub>, MnO, and FeO concentrations of 36.63–37.46 wt%, 0.79–3.65 wt%, and 31.74–35.86 wt%, respectively. The SiO<sub>2</sub>, MnO, and FeO concentrations of garnets in 10TM-26-2 vary from 36.36 wt% to 37.22 wt%, 8.68 wt% to 10.90 wt%, and 22.93 to 26.36 wt%, respectively. While the grain in 10TM-26-1 vary from 36.23 wt% to 37.23 wt%, 4.29 wt% to 12.67 wt%, and 23.23 wt% to 30.02 wt%, respectively (Table 2).

As exhibited in the Figure 6, most of the garnet grains are plotted from the spectrum of spandite (spessartite–almandine) with compositions ranging from Alm<sub>49</sub>Gr<sub>31</sub> to Alm<sub>76.56</sub>Gr<sub>11</sub>. It is notable that no analysis is plotted in the field of spessartite + andradite + uvarovite.
Despite homogenously isotropic textures observed in these garnet grains by BSE imaging (Figure 5), we conduct two profiles of major elements to examine whether they host chemical zonings. As a result, one garnet grain in 10TM-26-2 shows remarkable chemical zoning (Figure 5A). From core to rim, the almandine shows a significant increasing trend (56.30 mole % for rim and 49.31 mole % for core), but spessartine and grossularite show a decreasing trend from rim to core.

Different major elements show different spatial distribution pattern in the major elemental profiles (Figure 5B). Manganese (Mn) element is relatively enriched in the core, but iron (Fe) is enriched in the rim. In contrast, the elements of magnesium (Mg) and aluminum (Al) show no significant compositional variation from core to rim. Furthermore, the ratios of iron to magnesium (expressed by FeO/MgO) present significantly higher contents from core to rim, which is consistent with the compositional variations of spessartite and andradite.

Notably, the almandine, grossularite, and pyrope components in garnet grains are heterogeneous from core to rim. For 10TM-26-1, the contents of almandine range from 57.39 mole (%) to 64.41 mole (%) that decreases slightly from rim to core, and then decreases from core to rim (Figure 5B, Table 4). By comparison, the spessartite and andradite increase from rim to core, and then decrease from core to rim. The FeO/MnO ratios vary consistently to the almandine, grossularite, and pyrope variations. Moreover, FeO/MgO ratio variations are analogous to spessartite and andradite variations. The contents

### TABLE 1 | Sampling description of two garnet generations in the Tiemurt deposit.

| Sample No. | Position     | Mineral assemblage                        | Size   | Shape          | Color  |
|------------|--------------|-------------------------------------------|--------|----------------|--------|
| 10TMZK-49  | No. 4 ore    | Garnet, chlorite, biotite, amphibole, chalcophyrite, pyrite, and galena | 0.5-5 cm | Euuhedral to subhedral | Reddish |
| 10TM-26-2  | No. 27 ore   | Garnet, calcite, chlorite, chalcophyrite, sphalerite, and pyrite | 0.01-0.3 cm | Euhedral to subhedral | Reddish |
| 10TM-26-1  | No. 27 ore   | Garnet, chlorite, calcite, chalcophyrite, sphalerite, and pyrite | 0.01-0.3 cm | Euhedral to subhedral | Reddish |

**FIGURE 5 | Backscattered electron (BSE) imaging coupled with EPMA analysis on major elements profiles for Grt1 (10TM-26-2 and 10TM-26-1).**
### TABLE 2 | EMPA geochemical data (wt%) of the Tiemurt garnets.

| No. | 10TMZK-49-G1 | 10TMZK-49-G2 |
|-----|-------------|-------------|
| Id  | 1 | 2 | 3 | 4 | 5 | 6 | 1 | 2 | 3 | 4 | 5 | 6 |
| SiO₂ | 37.46 | 36.97 | 37.19 | 36.80 | 36.63 | 36.68 | 36.96 | 37.24 | 37.08 | 37.02 | 36.98 | 37.06 | 36.92 |
| TiO₂ | 0.04 | 0.03 | 0.02 | 0.00 | 0.00 | 0.01 | 0.03 | 0.04 | 0.02 | 0.00 | 0.00 | 0.00 | 0.05 |
| Al₂O₃ | 20.68 | 20.52 | 20.50 | 20.00 | 20.37 | 20.14 | 20.38 | 20.59 | 20.48 | 20.61 | 20.70 | 20.44 | 20.41 |
| Cr₂O₃ | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| FeO | 33.23 | 33.34 | 33.90 | 33.24 | 32.22 | 31.74 | 33.69 | 34.25 | 34.10 | 34.86 | 34.23 | 33.01 | 33.60 |
| MnO | 3.30 | 2.86 | 2.93 | 2.41 | 3.64 | 3.65 | 2.97 | 1.74 | 1.39 | 0.79 | 1.75 | 2.99 | 2.51 |
| MgO | 0.92 | 0.90 | 0.90 | 0.83 | 0.89 | 0.92 | 0.89 | 1.54 | 1.44 | 1.73 | 1.32 | 0.88 | 0.85 |
| CaO | 5.09 | 5.33 | 6.00 | 6.87 | 6.21 | 6.50 | 6.09 | 6.00 | 6.48 | 5.26 | 6.26 | 6.39 | 6.28 |
| Total | 101.73 | 101.04 | 101.50 | 99.97 | 99.66 | 101.00 | 101.20 | 100.99 | 101.27 | 101.23 | 100.77 | 100.61 |
| Si | 2.99 | 2.97 | 2.98 | 2.98 | 2.98 | 2.99 | 2.98 | 2.98 | 2.97 | 2.96 | 2.96 | 2.99 | 2.98 |
| Ti | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Al | 1.94 | 1.94 | 1.94 | 1.95 | 1.95 | 1.93 | 1.93 | 1.94 | 1.93 | 1.95 | 1.94 | 1.95 | 1.94 |
| Cr | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fe³⁺ | 0.06 | 0.07 | 0.08 | 0.07 | 0.06 | 0.08 | 0.08 | 0.07 | 0.08 | 0.07 | 0.07 | 0.07 | 0.07 |
| Fe²⁺ | 2.16 | 2.17 | 2.20 | 2.18 | 2.12 | 2.08 | 2.19 | 2.22 | 2.20 | 2.32 | 2.22 | 2.15 | 2.20 |
| Mn | 0.22 | 0.19 | 0.20 | 0.17 | 0.25 | 0.25 | 0.20 | 0.12 | 0.09 | 0.05 | 0.12 | 0.20 | 0.17 |
| Mg | 0.11 | 0.10 | 0.11 | 0.10 | 0.11 | 0.11 | 0.11 | 0.16 | 0.17 | 0.21 | 0.16 | 0.11 | 0.10 |
| Ca | 0.52 | 0.56 | 0.52 | 0.59 | 0.54 | 0.57 | 0.53 | 0.51 | 0.56 | 0.45 | 0.54 | 0.55 | 0.54 |
| Ura | 0.00 | 0.01 | 0.01 | 0.04 | 0.04 | 0.06 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 |
| And | 3.06 | 3.53 | 3.77 | 3.25 | 3.19 | 3.80 | 3.99 | 3.42 | 4.09 | 3.86 | 3.45 | 3.44 | 3.46 |
| Pyr | 3.63 | 3.16 | 3.55 | 3.29 | 3.56 | 3.69 | 3.49 | 5.31 | 5.67 | 6.81 | 5.18 | 3.49 | 3.40 |
| Spe | 7.42 | 6.44 | 6.59 | 5.45 | 8.29 | 8.34 | 6.70 | 3.91 | 3.13 | 1.77 | 3.90 | 6.77 | 5.70 |
| Gro | 14.23 | 15.06 | 13.31 | 16.03 | 14.85 | 14.95 | 13.40 | 13.64 | 14.30 | 11.00 | 14.22 | 14.84 | 14.55 |
| Amm | 71.66 | 71.80 | 72.78 | 71.94 | 70.27 | 69.15 | 72.43 | 73.73 | 72.80 | 76.56 | 73.24 | 71.46 | 72.89 |
| Other | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Note: All the calculations are based on 12 oxygen. Abbreviations: Ura-uracovite, And-andradite, Pyr-pyrope, Spe-speissartine, Gro-grossular, Amm-amlandine, and Amp-amphibole. **-**: Below the detection limit.

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of FeO are higher in core than rim, but its variations from rim to core are different. Distinctively, MnO is weakly zoned in core and it varies consistently to the FeO/MgO variations. While Al₂O₃ and MgO concentrations show no spatial variations from core to rim.

**Amphibolite**

Somewhat amounts of amphibole grains coexist with garnet grains in 10TMZK-49 (Figure 4), and two analyses of their compositions are listed in Table 3. They contain major compounds of SiO₂, MgO, Al₂O₃, MnO, and...
FeO contents up to 40.51–51.94 wt%, 4.67–11.70 wt%, 0.32–15.01 wt %, 0.18–0.73 wt%, and 23.45–33.25 wt%, respectively.

Trace Elemental Compositions

A total of thirty (30) trace elements analyses were conducted on garnet grains in the three samples, including 10 spots in 10TMZK-49, and 20 spots in 10TM-26-1 and 10TM-26-2. The results are listed in the Table 5, and the spike diagrams of rare earth elements (REEs) are plotted in the Figure 7, and the spike and statistical column diagrams of trace elements are displayed in the Figure 8.

The garnet grains in three samples show similar chondrite-normalized REE patterns. High rare-earth elements (HREE) are relatively enriched with the \( \sum \) HREE values of 21.43–101.98 ppm (mean = 41.65 ppm). Moreover, the values of \( \sum \) LREE/\( \sum \) HREE is extremely low (0.03–0.13, mean = 0.07). The feature of cerium negative anomaly (\( \delta \text{Ce} = 0.11–4.17 \), mean = 0.58) and europium positive anomalies (Eu/Eu* = 1.28–2.57, mean = 1.66) is also identified.

In addition, the large-ion lithophile elements (LILE) are extremely depleted in all garnet grains, with negligible amounts of Rb, Sr, and Ba, much lower than the value of average primitive mantle (Sun and McDonough, 1989; Figure 8). By contrast, the high-field elements (HFS), such as Th, Zr, and Y, are relatively enriched in the Tiemurt garnet than the values of average primitive mantle (Figure 8). As for the trace elements of P, Sm, and Ti, both the Tiemurt garnet and average primitive mantle show no obvious distinction in concentrations (Figure 8).

DISCUSSION

Mineral Growth History and Origin of Garnet

The systematic textural and chemical characteristics provide solid evidence for our discussion on mineral growth history and origin of the Tiemurt gem-grade garnet grains (Vander and Andre, 1991; Zhao et al., 1999; Martin et al., 2011). During the mineral growing, the garnet can grow to geo grade under the conditions of 1) the adequate influx supplying and 2) large enough growth space (Hickmott and Spear, 1992; Baxter et al., 2013). Our garnet displays relatively coarse and euhedral grains (Figure 3A), indicative of a well-supplied open space. However, the origin of Tiemurt garnet, such as mantle, ocean crust, skarn metasomatism, sedimentary exhalation, or metamorphism, needs to be discussed in detail (Gemmell et al., 1992; Hoal et al., 1994; Burton et al., 1999).

In the skarn deposit, the magmatic-hydrothermal fluids replace host carbonates to facilitate growth of gem-grade garnet (Jeremy and Hamid, 2013). In this case, the skarn garnet universally hosts some clear occasional zonation because of the relatively low rate of the metasomatic process (Vander and Andre, 1991; Park et al., 2017). In fact, the growth rate also acts as an important factor in controlling the grain size as well as the zonation pattern of garnet (Jamtveit and Hervig, 1994; García-Ruíz and Otálora, 2015). No textual zonation in the Tiemurt garnet implies a relatively high growth rate, which also exclude their possibility of magmatic-hydrothermal origin analogy to skarn (Jamtveit, 1991; Jamtveit et al., 1993; Zang et al., 2019).

The chemical compositions further provide reliable evidences for the garnet origin (Zhai et al., 2014; An et al., 2017). It is consensus that an abundance of Fe and Mn is distributed in the seawater, and therefore the garnet with sedimentary exhalation origin is Fe and Mn rich for their incorporation into the garnet crystal lattices (Gemmell et al., 1992; Burton et al., 1999). For the Tiemurt garnet, the feature of Al and Fe rich but Ca and Mn depleted are not products of seafloor sedimentation (Zheng et al., 2013a). Considering that no rocks related to the mantle transition zone or subducting ocean crust have been reported in the region, the only possible origin for the Tiemurt garnet is metamorphic.

In fact, the variations of geological occurrence, mineral assemblages, mineralogy, textures, and chemistry between Grt1 and Grt2 are just caused by the orogeny-related metamorphism and deformation (Chen et al., 2012; Zheng et al., 2013a).
In the early stage of orogenesis, the wall rocks are highly foliated to form garnet schists (Grt1). As the orogenesis continues, the ongoing structural development and accompanying large-scale fluid activities cause destruction of Grt1 and Grt2 precipitations in the larger host space. This mineral growth process is recorded by the variations of grain size, micromineral inclusions, and mineral assemblages between Grt1 and Grt2.

### TABLE 4 | EMPA geochemical data (wt%) of the two generation garnet profiles.

| No. | 10TM-26-2-G2 | 10TM-26-1-G2 |
|-----|--------------|--------------|
| Id  | 1 (Rim) | 2 | 3 | 4 | 5 (Core) | 6 (Core) | 7 | 8 | 9 | 10 (Rim) | 1 | 2 | 3 | 4 | 5 (Core) | 6 (Core) | 7 | 8 | 9 | 10 (Rim) |
| SiO₂ | 36.84 | 36.79 | 36.85 | 36.82 | 36.89 | 36.89 | 36.85 | 36.83 | 36.79 | 36.78 | 36.82 | 37.05 | 36.79 | 36.87 | 36.98 | 36.70 | 36.26 | 36.23 |
| TiO₂ | 0.02 | 0.06 | 0.04 | 0.03 | 0.04 | 0.04 | 0.04 | 0.07 | 0.09 | 0.05 | 0.04 | 0.06 | 0.05 | 0.03 | 0.03 | 0.04 | 0.06 | 0.09 | 0.09 |
| Al₂O₃ | 20.36 | 20.27 | 20.29 | 20.19 | 20.42 | 19.90 | 20.30 | 20.02 | 20.36 | 20.34 | 20.27 | 20.42 | 20.30 | 20.02 | 20.36 | 20.34 | 20.34 |
| Cr₂O₃ | 0.03 | 0.02 | 0.02 | 0.00 | 0.01 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| FeO | 25.61 | 24.96 | 24.39 | 23.74 | 22.96 | 24.39 | 24.20 | 24.64 | 25.22 | 26.22 | 24.96 | 24.39 | 23.74 | 22.96 | 24.39 | 24.20 | 24.64 | 25.22 |
| MnO | 9.16 | 9.71 | 10.47 | 10.44 | 10.69 | 10.45 | 10.90 | 10.73 | 9.86 | 8.69 | 9.16 | 9.71 | 10.47 | 10.44 | 10.69 | 10.45 | 10.90 | 10.73 | 9.86 |
| MgO | 1.10 | 1.06 | 0.97 | 0.96 | 0.94 | 0.96 | 0.96 | 0.98 | 1.06 | 1.20 | 1.10 | 1.06 | 0.97 | 0.96 | 0.94 | 0.96 | 0.96 | 0.98 | 1.06 | 1.20 |
| CaO | 7.12 | 7.31 | 7.32 | 7.41 | 7.46 | 7.82 | 7.25 | 6.81 | 7.01 | 6.68 | 7.12 | 7.31 | 7.32 | 7.41 | 7.46 | 7.82 | 7.25 | 6.81 | 7.01 | 6.68 |
| Total | 100.24 | 100.16 | 100.35 | 99.76 | 100.17 | 98.48 | 100.52 | 100.06 | 100.35 | 99.97 |
| Si | 2.97 | 2.97 | 2.97 | 2.98 | 2.98 | 2.98 | 2.98 | 2.98 | 2.98 | 2.98 | 2.97 | 2.97 | 2.97 | 2.98 | 2.98 | 2.98 | 2.98 | 2.98 | 2.98 |
| Ti | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Al | 1.94 | 1.93 | 1.93 | 1.94 | 1.94 | 1.92 | 1.93 | 1.91 | 1.94 | 1.94 | 1.94 | 1.93 | 1.94 | 1.93 | 1.94 | 1.93 | 1.91 | 1.94 | 1.94 |
| Cr | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fe³⁺ | 0.08 | 0.09 | 0.09 | 0.08 | 0.07 | 0.09 | 0.09 | 0.10 | 0.08 | 0.07 |
| Fe²⁺ | 1.65 | 1.60 | 1.56 | 1.54 | 1.53 | 1.49 | 1.54 | 1.57 | 1.62 | 1.70 |
| Mn | 0.63 | 0.66 | 0.72 | 0.73 | 0.73 | 0.73 | 0.74 | 0.74 | 0.67 | 0.60 |
| Mg | 0.13 | 0.13 | 0.12 | 0.12 | 0.11 | 0.12 | 0.12 | 0.12 | 0.13 | 0.15 |
| Ca | 0.62 | 0.63 | 0.63 | 0.64 | 0.64 | 0.69 | 0.63 | 0.63 | 0.59 | 0.58 |
| FeO/MgO | 23.26 | 23.68 | 23.15 | 24.85 | 25.31 | 24.12 | 25.10 | 25.17 | 23.79 | 21.78 |
| Ura | 0.09 | 0.06 | 0.05 | 0.00 | 0.03 | 0.01 | 0.00 | 0.08 | 0.06 |
| And | 3.87 | 4.23 | 4.29 | 4.07 | 3.90 | 4.25 | 4.45 | 4.90 | 4.06 | 3.66 |
| Pyr | 4.38 | 4.21 | 3.86 | 3.85 | 3.74 | 3.86 | 3.83 | 3.92 | 4.21 | 4.81 |
| Spe | 5.61 | 7.15 | 6.28 | 5.83 | 4.52 | 4.29 | 5.94 | 6.51 | 5.94 | 6.51 |
| Gro | 16.40 | 16.62 | 16.59 | 17.27 | 17.82 | 18.42 | 18.24 | 16.24 | 14.63 | 15.96 |
| Alm | 54.56 | 52.92 | 51.56 | 51.04 | 50.72 | 49.31 | 50.91 | 52.09 | 53.50 | 56.30 |
| Other | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Note: All the calculations are based on 12 oxygens. Abbreviations: Ura-uvarovite, And-andradite, Pyr-pyrope, Spe-speissartine, Gro-grossular, Alm-almandine, and Amph-amphibole. "-": Below the detection limit.
Physicochemical Condition Recorded by Garnet

Under the metamorphic environment, we can utilize the contents and variations of Ca, Mn, Fe, and Mg in garnet to evaluate the pressure (P)–temperature (T) condition (Andrew, 1994; Gerya et al., 1997). The principle is that the P-T condition has an impact on cooperation of these cations into crystal structures of garnet in relation with anions’ charge and radius (Shannon, 1976; Smith et al., 2004; Xia et al., 2016). For the same (II) charge substituting to the “A” location, the decreasing order of anions radius Ca2+ > Mn2+ > Fe2+ > Mg2+ is sensitive to reflect the fluctuation of the P-T condition (Zhou et al., 2014), that is, Ca-rich garnet formed in low-pressured contact metamorphism, Mn-Al-rich garnet formed in low-grade regional metamorphism, Fe-Al-rich garnet formed in relatively higher regional metamorphism, and Mg-rich garnet formed in high-pressured metamorphism (Yardley et al., 1991; Jamtveit et al., 1993; Crowe et al., 2001; Fernando et al., 2003). Therefore, the Tiemurt Fe-Al-rich garnet is formed in relatively higher regional metamorphism. In consideration of regional geology (Chen et al., 2012), the low-amphibolite to middle-greenschist facies are the preferred window for the Tiemurt garnet.

Amphibole is a common mineral of metasabasites from amphibolite to greenschist facies, and its composition changes regularly with metamorphic grade (Triboulet, 1992). The amphibole paragenetic with garnet allows us to calculate more accurate P-T condition (Gerya et al., 1997). Here, we adopt the methodology of Gerya et al. (1997) based on the Gibbs’ phase rule at mineral equilibrium (Holland and Blundy, 1994; Gerya et al., 1997). The calculation is based on the following formula derivation, that is,

$$ T(K) = \frac{6119 - 28.4P + 114X_{Mg}^{Hbl}}{8.181 - Rln(8.489 - S_{Hbl}^{P})} $$

$$ P(kbr) = \left[ \frac{2543 - 4.744T + 175X_{Mg}^{Hbl} + RTln(A_{Hbl}^{P} + 1.433)}{\times 148.1} \right] $$

where P = P, kbar; T = T, K; X_{Mg}^{Hbl} = Mg/(Fe + Mg), bulk Mg mole fraction of amphibole; and S_{Hbl} and A_{Hbl} are Si and Al in amphibole calculated on 13 cations.

The calculated temperature range of 10TMZK-49 is 640–643°C at the pressure of 5,218–5,900 bar (Table 6).

Additionally, we can use the distribution patterns of REE and trace elements to further deduce the acidity and redox condition (Sverjensky, 1984; Bau, 1991). It is suggested that REE fractionation is strongly dependent on the hydrothermal fluid pH (Bau, 1991), HREE enrichment, and LREE depletion with weak negative or no Eu anomalies indicating a nearly neutral environment. Garnet from the Tiemurt is characterized as HREE-rich, LREE-depleted, and weak positive Eu anomaly (Figure 7). Fractionation of HREE against LREE is controlled by the major compositions such as Al and Fe in garnet, and the weak positive Eu anomaly is caused by the metamorphic hydrothermal fluids under mildly acidic condition (Scherer et al., 2000; Peitermann et al., 2004; Schmidt et al., 2011; Cheng et al., 2012). In this case, the REE pattern is chiefly determined by the complex agents (e.g., Cl−) that enhance stability of Eu2+, rather than REE3+, in solution (Geiger et al., 1989; Ballaran et al., 1999), which can produce distinct positive Eu anomalies. The presence of chloride intergrown with garnet also supports the mildly acidic condition, which facilitates soluble Eu2+ transporting and substituting Fe2+ in garnet crystal to form distinctly positive Eu anomalies (Smith et al., 2004; Gaspar et al., 2008).

Another evidence is the concentrations of uranium, which is a redox-sensitive element with different valence states of U4+ and U6+ (Smith et al., 2004; Zhang et al., 2017b). The decrease of fO2 in the hydrothermal fluids reduces the solubility of U and increases the incorporation of U into Garnet. It means that the higher U contents of garnet may indicate the lower fO2 of hydrothermal fluids. At the Tiemurt, Grt1 has lower U contents (0.0002–0.19 ppm) than those of Grt2 (0.02–12.5 ppm), which partly indicate that Grt1 hosts higher fO2.

Additionally, the iron electrovalence ratio (Fe2+/Fe3+) is also an important oxygen fugacity indicator of garnet (Park et al., 2017; Liang et al., 2021). For the garnet A2B2(SiO4)3 formula, the cations of Fe2+ and Fe3+ can be accommodated into the crystal structure of A and B, respectively. For the B location, both Al3+ and Fe3+ can occupy together, and therefore Al-rich chemical composition can reduce the amount of Fe2+ (Jamtveit et al., 1993). In the Tiemurt garnet, Grt1 yields a more Al-rich chemical composition that can be calculated into the equal Fe2+/Fe3+ ratios of 15.9–23.1, distinct from Grt2 with a higher Fe2+/Fe3+ ratio of 21.1–83.3. Therefore, the variation of Fe2+/Fe3+ from Grt1 to Grt2 records a significant decreasing trend of oxygen fugacity at the Tiemurt.

Furthermore, the enrichment of Th, Y, and HREE indicates a relatively reduced condition in Grt2 (Gaspar, 2005). Taking the element of Th for an example, the decreasing fO2 value of the fluid system could reduce Th solubility in solution and in turn increase Th incorporation into garnet (Huang et al., 2014).

Metamorphic Garnet Linking With the Orogenic-Type Deposits in Altay

On the basis of above discussion, the garnets from the Tiemurt deposit are principally crystallized from the metamorphic hydrothermal fluids, and therefore the variations in garnet geochemistry are largely controlled by some external factors such as fluid compositions, fluid–rock interactions, and metasomatism dynamics (Jamtveit, 1991; Ottonello and Moretti, 1998; Gaspar et al., 2008). Grt1 and Grt2 host the similar fluid origin and fluid–rock interaction ratios, and therefore their chemical variations are possibly caused by metasomatism dynamics, that is, diffusive or infiltration metasomatism (Bau, 1991; Gaspar et al., 2008). The diffusive metasomatism will produce fluids with near-neutral pH and alteration products in which REE composition is buffered by reduced, mildly acidic, external-derived fluids, where chloride complexes...
### Table 5: Representative LA-ICP-MS data (ppm) of garnets from the Tiemurt deposit.

| No. | GT1 | GT2 |
|-----|-----|-----|
| **Trace element** | **Sr** | **Sr** |
| 1 | 0.021 | 0.024 |
| 2 | 0.000 | 0.000 |
| 3 | 0.000 | 0.000 |
| 4 | 0.033 | 0.014 |
| 5 | 0.011 | 0.007 |
| 6 | 0.010 | 0.006 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.042 | 0.037 |

**Sr**

| Trace element | **Rb** | **Rb** |
|---------------|-------|-------|
| 1 | 0.022 | 0.046 |
| 2 | 0.000 | 0.000 |
| 3 | 0.000 | 0.000 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.025 | 0.037 |

**Rb**

| Trace element | **Ba** | **Ba** |
|---------------|-------|-------|
| 1 | 0.000 | 0.000 |
| 2 | 0.000 | 0.000 |
| 3 | 0.000 | 0.000 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.000 | 0.000 |

**Ba**

| Trace element | **Th** | **Th** |
|---------------|-------|-------|
| 1 | 0.000 | 0.000 |
| 2 | 0.000 | 0.000 |
| 3 | 0.000 | 0.000 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.000 | 0.000 |

**Th**

| Trace element | **U** | **U** |
|---------------|-------|-------|
| 1 | 0.012 | 0.022 |
| 2 | 0.000 | 0.000 |
| 3 | 0.011 | 0.002 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.000 | 0.000 |

**U**

| Trace element | **Ta** | **Ta** |
|---------------|-------|-------|
| 1 | 0.000 | 0.000 |
| 2 | 0.000 | 0.000 |
| 3 | 0.000 | 0.000 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.000 | 0.000 |

**Ta**

| Trace element | **Nb** | **Nb** |
|---------------|-------|-------|
| 1 | 0.000 | 0.000 |
| 2 | 0.000 | 0.000 |
| 3 | 0.000 | 0.000 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.000 | 0.000 |

**Nb**

| Trace element | **P** | **P** |
|---------------|-------|-------|
| 1 | 33.537 | 40.304 |
| 2 | 40.304 | 40.537 |
| 3 | 40.537 | 32.427 |
| 4 | 32.427 | 34.267 |
| 5 | 34.267 | 38.722 |
| 6 | 38.722 | 38.034 |
| 7 | 38.034 | 36.842 |
| 8 | 36.842 | 32.796 |
| 9 | 32.796 | 37.750 |
| 10 | 37.750 | 40.190 |

**P**

| Trace element | **Zr** | **Zr** |
|---------------|-------|-------|
| 1 | 3.578 | 3.942 |
| 2 | 3.942 | 3.773 |
| 3 | 3.773 | 68.137 |
| 4 | 68.137 | 143.078 |
| 5 | 143.078 | 42.672 |
| 6 | 42.672 | 30.271 |
| 7 | 30.271 | 4.199 |
| 8 | 4.199 | 4.638 |
| 9 | 4.638 | 4.172 |
| 10 | 4.172 | 4.260 |

**Zr**

| Trace element | **Eu** | **Eu** |
|---------------|-------|-------|
| 1 | 0.016 | 0.040 |
| 2 | 0.040 | 0.058 |
| 3 | 0.058 | 1.766 |
| 4 | 1.766 | 3.072 |
| 5 | 3.072 | 1.204 |
| 6 | 1.204 | 0.674 |
| 7 | 0.674 | 0.102 |
| 8 | 0.102 | 0.119 |
| 9 | 0.119 | 0.045 |
| 10 | 0.045 | 0.000 |

**Eu**

| Trace element | **Ti** | **Ti** |
|---------------|-------|-------|
| 1 | 46.466 | 55.841 |
| 2 | 55.841 | 56.164 |
| 3 | 56.164 | 44.927 |
| 4 | 44.927 | 47.477 |
| 5 | 47.477 | 53.649 |
| 6 | 53.649 | 49.925 |
| 7 | 49.925 | 51.044 |
| 8 | 51.044 | 45.438 |
| 9 | 45.438 | 52.303 |
| 10 | 52.303 | 50.727 |

**Ti**

(Continued on following page)
can be important in Eu²⁺ transport (Bau, 1991; Yardley et al., 1991; Lottermoser, 1992).

Since the Tiemurt garnet formed under mildly acidic and relatively reduced condition, we inferred that they have formed by advective metasomatism (Gaspar, 2005), that is, diffusive metasomatism by fluids equilibrated with the host rocks. In this case, Grt1 and cores of Grt2 are formed by advective metasomatism, while rims of Grt2 are formed by the episodic inflections between infiltration metasomatism and advective metasomatism (Meinert et al., 2005; Dziggel et al., 2009).

As the Tiemurt garnets are spatially close to the polymetallic ores, their formation has potential to code the ore genesis of the Tiemurt deposit. A diversity of genetic types has been suggested for the ore genesis of the Pb–Zn–Cu–Au deposit in the Chinese

| TABLE 5 | (Continued) Representative LA-ICP-MS data (ppm) of garnets from the Tiemurt deposit. |
| No. | GT2 |
| Id | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Ho | 16.564 | 32.037 | 62.313 | 52.091 | 82.521 | 68.587 | 83.550 | 55.819 | 60.413 | 44.990 |
| Er | 23.856 | 42.635 | 84.099 | 65.940 | 129.771 | 109.202 | 115.769 | 76.993 | 85.242 | 64.704 |
| Yb | 34.537 | 63.975 | 131.639 | 99.817 | 239.726 | 205.976 | 190.661 | 122.911 | 156.172 | 105.187 |
| Lu | 39.003 | 71.522 | 147.388 | 113.165 | 278.668 | 247.076 | 223.939 | 159.362 | 182.381 | 122.095 |
| ΣREE | 226.121 | 372.613 | 675.667 | 560.998 | 1083.044 | 940.768 | 930.983 | 636.485 | 737.582 | 516.985 |
| LREE | 29.252 | 27.801 | 28.828 | 34.780 | 37.194 | 37.633 | 37.027 | 31.232 | 32.383 | 27.922 |
| HREE | 196.869 | 344.812 | 646.839 | 526.218 | 1045.850 | 903.135 | 893.956 | 605.253 | 705.199 | 516.985 |
| LREE/HREE | 0.149 | 0.081 | 0.045 | 0.066 | 0.036 | 0.042 | 0.041 | 0.052 | 0.046 | 0.054 |
| LaN/YbN | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| δEu | 5.331 | 4.856 | 4.433 | 4.430 | 4.263 | 4.759 | 4.440 | 4.900 | 4.773 | 4.357 |
| δCe | 0.044 | 0.078 | 0.177 | 0.177 | 0.177 | 0.177 | 0.177 | 0.177 | 0.177 | 0.177 |

Note: REE normalized to chondrite (Sun and McDonough, 1989). *-* Below the detection limit.

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Altay Orogen, such as VMS, metamorphosed VMS, and orogenic-type deposits (Xu et al., 2008; Xu et al., 2011; Wan et al., 2010a; Zhang et al., 2012; Zheng et al., 2013b). The key to resolve these disagreements lies in the origin of their ore fluids. The metamorphic garnet supporting the polymetallic deposits are orogenic-type, and therefore the eventual metal accumulation is attributed for the orogeny-related metamorphism and deformation, as well as the metamorphic hydrothermal fluids’ activities.

**CONCLUSION**

1) Two categories of almandine (Fe-Al–garnet), Grt1 and Grt2, both have similar major elemental compositions (such as SiO$_2$, Al$_2$O$_3$, and CaO), chondrite-normalized REE patterns (HREE-enriched, LREE-depleted, Ce negative anomaly, and Eu positive anomalies), depleted lithophile elements, and enriched high-field elements.

2) The sub- to euhedral mineral inclusion–rich Grt1 is intergrown with amphibolite, chlorite, and biotite; the sub- to euhedral mineral poor Grt2 is paragenetic with quartz, calcite, chlorite, and biotite. Grt1 and Grt2 assembles and trace elements recorded a methosthermal, high-pressured, mildly acidic, and reductive condition.

3) Grt1 and cores of Grt2 are formed by advective metasomatism, while rims of Grt2 are formed by the episodic inflections between infiltration metasomatism and advective metasomatism, and their formation linking with orogeny-type regional metamorphism as well as the metamorphic hydrothermal fluids’ activities.

**DATA AVAILABILITY STATEMENT**

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

**AUTHOR CONTRIBUTIONS**

ZH prepared samples for analysis, performed initial data analysis, and took the lead on writing the manuscript. YZ and PY wrote the final version of the manuscript. ZH was responsible for the statistical treatment of the data. YZ, YW, and CW took part in the fieldwork and developing the original ideas.

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