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EDITED BY

Chen Zhao,
Shenyang Center of China Geological
Survey, China

REVIEWED BY

Xin Jin,
Zhejiang Ocean University, China
Zhanzhan Duan,
Hebei GEO University, China

*CORRESPONDENCE

Shangjing Wu,
✉ wushj25@hynu.edu.cn
Hengzhong Qiao,
✉ qiaohzh@lsnu.edu.cn

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Timing of retrograde metamorphism in medium-pressure pelitic granulites of the Qianlishan Complex: insights from monazite-zircon U-Pb geochronology and phase equilibria modelling

Shangjing Wu^{1*}, Yige Su¹, Qin Wang¹ and Hengzhong Qiao^{2*}

¹College of Geography and Tourism, Hengyang Normal University, Hengyang, China, ²College of Tourism and Geographical Science, Leshan Normal University, Leshan, China

Accurately determining the retrograde metamorphic ages of pelitic granulites is crucial for reconstructing their metamorphic evolution and understanding associated post-collisional extensional and subsequent exhumation processes in orogenic belts. This study integrates zircon and monazite geochronology with thermodynamic modelling to determine the retrograde metamorphic history of medium-pressure (MP) pelitic granulites in the Qianlishan Complex of the Khondalite Belt, North China Craton. Our findings show that all MP pelitic granulites follow similar clockwise pressure-temperature (P-T) trajectories, with precisely defined post-peak P-T conditions of 775°C–825°C and 4.9–6.5 kbar. U-Pb zircon dating via LA-ICP-MS on three MP granulites produced metamorphic ages of 1943 ± 18 Ma, 1931 ± 10 Ma, and 1941 ± 10 Ma. Similarly, monazite U-Pb analyses of the same samples yielded ages of 1932 ± 3 Ma, 1935 ± 3 Ma, and 1939 ± 3 Ma. A well-matched set of dates indicates a metamorphic episode at ~ 1.93 Ga, which established a metamorphic period during the granulite-facies retrograde cooling phase. The geochronological studies of pelitic granulites from the Qianlishan Complex indicate that a peak-pressure metamorphic event took place between 1.96 and 1.94 Ga, with subsequent decompression and retrograde cooling occurring around 1.93 Ga. These findings reinforce the hypothesis that a continent-continent collision occurred in the Khondalite Belt around 1.95 Ga, followed by a rapid slab-breakoff at shallow depths, which triggered the uplift of pelitic granulites in the western Khondalite Belt to mid-crustal levels and their subsequent cooling around 1.93 Ga.

KEYWORDS

monazite-zircon U-Pb dating, phase equilibria modelling, pelitic granulite, Khondalite Belt, North China Craton

1 Introduction

As key accessory minerals in metamorphic rocks, zircon and monazite play a vital role in geochronology, providing critical insights into the timing of metamorphism and the thermal and tectonic history of high-grade terrains (Parrish, 1990; Rubatto et al., 2001; Rubatto et al., 2013; Kohn and Malloy, 2004; Harley et al., 2007; Johnson et al., 2015; Jiao et al., 2020). Their effectiveness stems from the U-Pb system's ability to preserve records of polyphase metamorphic evolution, even under relatively high-temperature conditions (Rubatto et al., 2001). Compared to zircon, monazite effectively excludes common Pb during its growth, minimizing initial Pb interference while also exhibiting strong resistance to Pb diffusion loss and high tolerance to radiation damage (Seydoux-Guillaume et al., 2002; Cherniak et al., 2004). Furthermore, with a lower closure temperature ($\sim 725^{\circ}\text{C}$; Parrish, 1990) than zircon ($>900^{\circ}\text{C}$; Cherniak and Watson, 2001), monazite is more prone to recrystallization and age resetting during high-grade metamorphism, allowing it to effectively record multiple metamorphic stages, and thus serving as a valuable tool for unraveling the complex histories of polyphase metamorphic terrains (Dewolf et al., 1993; Catlos et al., 2002; Gibson et al., 2004; Kohn and Malloy, 2004; Mahan et al., 2006; Zhang et al., 2012). Given these distinctions, using zircon and monazite in geochronological studies offers complementary insights (Rubatto et al., 2013).

The Qianlishan Complex is located in the western Khondalite Belt (Figure 1) and contains predominantly medium-pressure (MP) pelitic granulites interspersed with occasional high-pressure (HP) pelitic and felsic granulites (Yin et al., 2014; Wu et al., 2020). Extensive research has been conducted on the pressure-temperature (P-T) evolution and peak metamorphic timing of high-pressure (HP) granulites within the Qianlishan Complex (Yin et al., 2009; Yin et al., 2014; Wu et al., 2020). The observed clockwise P-T trajectories, along with a zircon metamorphic dating at approximately 1.95 Ga, offer compelling evidence to support a continental collision between the Yinshan and Ordos Blocks, which led to the formation of the Khondalite Belt at ~ 1.95 Ga (Yin et al., 2009; Yin et al., 2014; Qiao et al., 2016; Wu et al., 2020). Despite their widespread occurrence, MP granulites have received relatively limited focus. As representative lithologies of the middle-lower crust, these rocks are of fundamental significance, preserving crucial evidence of multistage metamorphic evolution, especially retrograde processes. Deciphering their metamorphic history is key to reconstructing the timing and geodynamic mechanisms of post-collisional extensional and subsequent exhumation processes in the Khondalite Belt.

This study investigates three representative MP pelitic granulite samples from the Qianlishan Complex. Petrographic observations, together with phase equilibrium modelling, were employed to analyze the metamorphic history of these rocks by focusing on retrograde segments of the P-T path, including decompression and cooling. Furthermore, this study integrates the U-Pb dating of monazite and zircon to determine geochronological data for the first time regarding the MP pelitic granulites within the Qianlishan Complex, offering valuable insights into the timing of retrograde cooling metamorphism. These findings establish complete P-T-t trajectories of pelitic granulites and enhance deeper understanding of the tectonic evolution of the Khondalite Belt.

2 Geological background

The North China Craton (NCC) exists as an ancient craton that formed through Archean crustal development followed by reorganizational processes, with micro-blocks distributed along Paleoproterozoic linear structural belts (Zhao et al., 2012; Zhai, 2014). Located in the NCC, the Khondalite Belt represents a significant Paleoproterozoic orogenic belt with an east-west orientation, delineating the Yinshan Block from the Ordos Block in the Western Block (Figure 1). The belt consists of, from east to west, the Jinjing Complex, the Wulashan-Daqingshan Complex, and the Qianlishan-Helanshan Complex (Figure 1). Khondalites, defined by their assemblage of primarily Al-rich gneisses, calc-silicate rocks, marbles, and garnet-bearing quartzites, form the dominant lithologies within these complexes (Condie et al., 1992; Lu et al., 1996; Zhai, 2022). These Khondalites are accompanied by minor mafic granulites, charnockites, S-type granites, and tonalite-trondhjemite-granodiorite gneiss (Peng et al., 2010; Peng et al., 2012; Dan et al., 2012; Liu et al., 2014; Wang et al., 2018). The Khondalite Belt has undergone a complex tectonothermal history, involving successive stages of metamorphism, magmatism, and deformation (Yin et al., 2023). This evolution began with subduction-related processes and culminated in continental collision followed by post-orogenic extensional tectonics (Yin et al., 2023). Two distinct types of metamorphism involving HP metamorphism (Zhou et al., 2010; Yin et al., 2014; Yin et al., 2015; Wu et al., 2020; Liu et al., 2017) and ultra-high-temperature (UHT) metamorphism (Santosh et al., 2007; Santosh et al., 2012; Jiao et al., 2011; Jiao et al., 2017; Jiao et al., 2020; Jiao and Guo, 2011; Guo et al., 2012; Liu et al., 2012; Yang et al., 2014; Li and Wei, 2016; Li and Wei, 2018; Gou et al., 2018; Gou et al., 2019; Li et al., 2019; Wu et al., 2024) have been identified within the belt. In a recently developed geodynamic model, the complex thermal evolution of UHT metamorphism, characterized by alternating heating and cooling cycles, is explained as the result of two discrete episodes of lithospheric extension (Qi et al., 2024).

At the westernmost of the Khondalite Belt lies the Qianlishan Complex, a metamorphic complex exhibiting upper amphibolite-to granulite-facies conditions. Its primary constituents include Khondalites and Paleoproterozoic multistage granitic plutons (Lu et al., 1996; Li et al., 2022). In this region, the Khondalites are grouped under the Qianlishan Group, which comprises the Qianligou, Habuqigai, and Chaganguole Formations (Figure 2). Following their deposition at approximately 2.0–1.95 Ga, the protoliths of the Qianlishan Group experienced a granulite-facies peak metamorphic event around 1.95 Ga (Yin et al., 2009; Qiao et al., 2016; He et al., 2017; Wu et al., 2020). This metamorphism is primarily characterized by HP pelitic granulites that contain a peak mineral assemblage of garnet, kyanite, plagioclase, biotite, K-feldspar, and quartz (Yin et al., 2014; Wu et al., 2020). Metamorphic investigations indicate that these HP pelitic and felsic granulites in the Qianlishan Complex share a broadly similar clockwise P-T trajectory, peaking at conditions of 11–15 kbar and 800°C – 850°C (Yin et al., 2014; Wu et al., 2020). The tectono-magmatic evolution of the complex also includes three main magmatic events at ~ 2.06 Ga, ~ 1.95 Ga, and ~ 1.92 Ga (Li et al., 2022). Two significant deformation phases are also documented: The first (D1) occurred between 1.98 and 1.93 Ga,

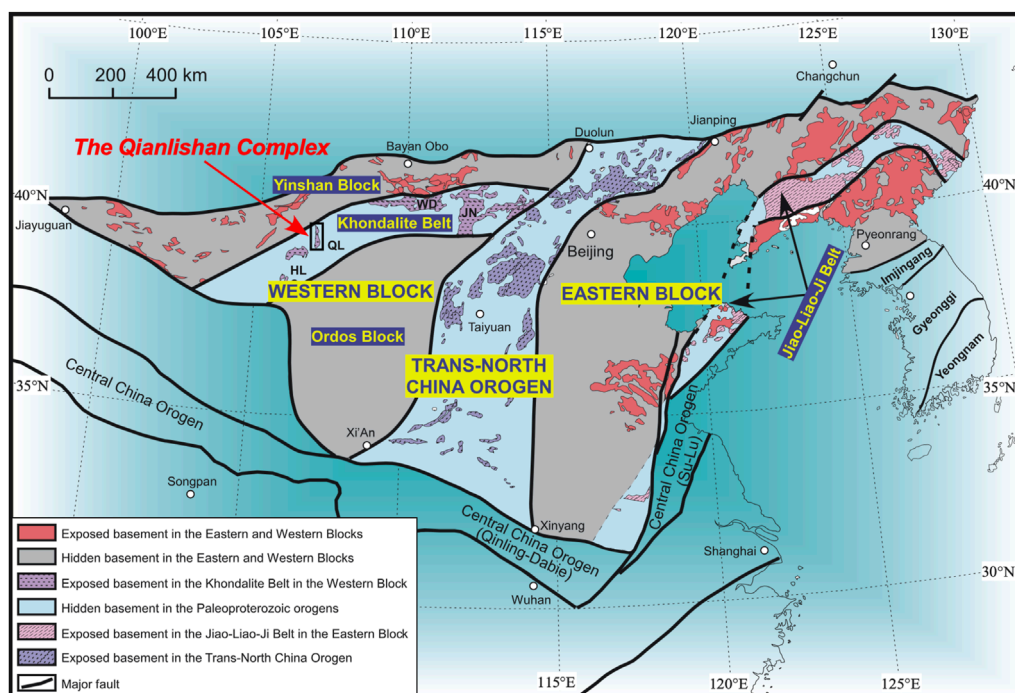


FIGURE 1

Simplified tectonic framework of the North China Craton (NCC, modified after Zhao et al., 2005). Abbreviations: HL, Helanshan Complex; QL, Qianlishan Complex; WD, Wulashan-Daqingshan Complex; JN, Jinling Complex.

while the second (D2) took place between 1.93 and 1.90 Ga (Yin et al., 2020).

3 Field sampling

Three MP pelitic granulite samples, designated as 23QL08-1, 23QL11-1, and 23QL16-1, were gathered from the Qianlishan Complex. The sampling sites are shown in Figure 2. On an outcrop scale, these pelitic granulite samples exhibit well-developed gneissic foliations and a distinct interlayered texture with felsic granulites and felsic dykes (Figure 3). At the hand specimen scale, the dark gray pelitic granulites exhibit abundant garnet and display signs of significant partial melting, manifested by localized accumulations of melt that form veins and patches (Figure 3).

4 Methods

4.1 Bulk-rock composition

A Rigaku ZSX Primus II wavelength-dispersive X-ray fluorescence (XRF) spectrometer was used at Guangzhou Tuoyan Analytical Technology Co., Ltd., Guangzhou, China, to analyze the primary elemental compositions of three MP pelitic granulite samples. To ensure measurement accuracy, we employed GSR-3/4/6, OU-6, GSR/13, and NOD-P-1 for quality control. The analytical precision was maintained within a relative standard deviation not exceeding 5%.

4.2 U-Pb dating of zircon and monazite

We extracted zircon and monazite from three MP pelitic granulite samples by use of heavy liquid and magnetic techniques, with final grain selection conducted manually. Grains were embedded in epoxy, polished, and analyzed under reflected and transmitted light to view internal textures. Zircon grain internal features became visible through cathodoluminescence (CL) imaging, while the monazite structure became visible through backscattered electron (BSE) imaging.

Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) analyses for U-Pb isotopes and trace elements were undertaken at Guangzhou Tuoyan Analytical Technology Co., Ltd., Guangzhou, China. Then the NWR 193 nm ArF excimer laser system, coupled with Agilent 8900 quadrupole ICP-MS was used for the analysis through an ablation system set at 25 μm for zircon and 30 μm for monazite, at a laser repetition rate of 6 Hz.

Zircon U-Pb dating used the 91500 standard (Wiedenbeck et al., 1995), while trace elements were measured by use of the NIST SRM 610 glass (Reed, 1992) for calibration. Data reliability was achieved through analyses of two secondary reference materials: zircon Plešovice (Sláma et al., 2008) and Tan-Z (Hu et al., 2021). The analytical procedures adhered to the methodologies established by Yuan et al. (2004) and Chu et al. (2020). The dating of monazite samples relied on monazite 44069 (Aleinikoff et al., 2006) for correcting instrumental mass bias and elemental fractionation effects. The trace element calibration employed standard reference materials, NIST SRM 610 and BCR-2G (Jochum et al., 2011).

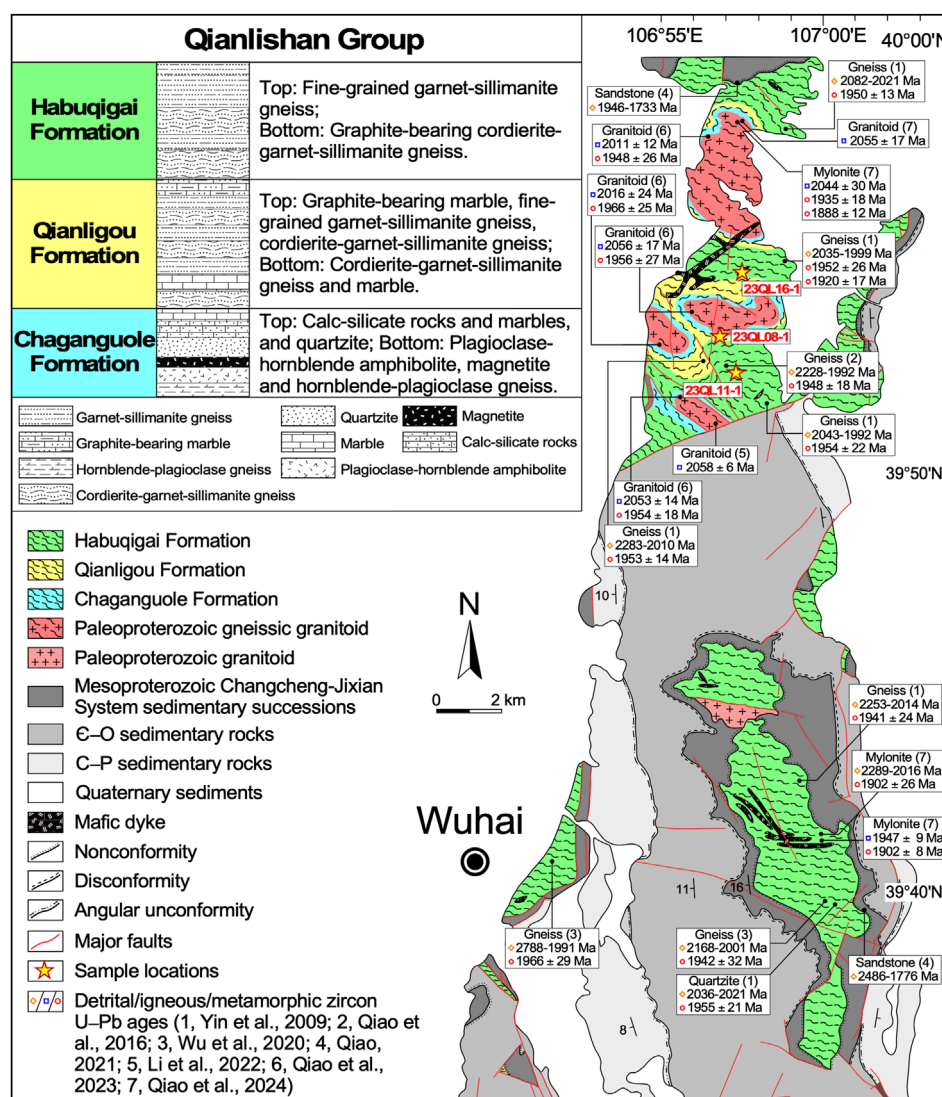


FIGURE 2

Geological overview of the Qianlishan Complex, modified from Yin et al. (2011) and Qiao et al. (2024), showing the sampling sites of MP pelitic granulite. U-Pb zircon ages for detrital, igneous, and metamorphic events are referenced from Yin et al. (2009), Qiao et al. (2016), Qiao et al. (2023), Qiao et al. (2024), Qiao (2021), Wu et al. (2020) and Li et al. (2022).

Data processing, including background signal subtraction, integration of analytical spectra, and time-drift corrections, was implemented by use of Iolite 4.0. The U-Pb age calculations with intercept age or weighted mean age determination came from Isoplot R (Vermeesch, 2018). Supplementary Tables S1,S2 provide the entire U-Pb age data set from zircon and monazite analyses in this study.

5 Results

5.1 Petrography

The three MP granulite samples exhibit distinct mineralogical compositions (Figure 4). In sample 23QL08-1 (Figures 4A,B), K-feldspar is the dominant phase (~40 vol%), followed by quartz (~20 vol%) and biotite (~15 vol%). It also contains moderate

amounts of sericitized cordierite (~12 vol%) and plagioclase (~8 vol%), with lesser amounts of garnet (~3 vol%) and sillimanite (~2 vol%). In contrast, Sample 23QL11-1 (Figures 4C,D) is dominated by sillimanite (~30 vol%), followed by K-feldspar, quartz, and cordierite, each making up approximately 15 vol%. It also contains notable garnet (~12 vol%) and biotite (~10 vol%), with a small amount of plagioclase (~2 vol%). Meanwhile, Sample 23QL16-1 (Figures 4E,F) features a high proportion of cordierite (~30 vol%) and sillimanite (~20 vol%). It has significant quartz and biotite, each comprising around 15 vol%, moderate K-feldspar (~12 vol%), minor garnet (~7 vol%), and a trace amount of plagioclase (~1 vol%). All three samples contain monazite, zircon, and ilmenite as minor accessory phases. Despite their differing mineralogical compositions, the three samples share remarkably similar mineral assemblages. Garnet is found as subhedral crystals and has undergone replacement by cordierite in all three samples



FIGURE 3
Representative outcrop images of MP pelitic granulites and their surrounding wall rocks in the Qianlishan Complex: (A, B) 23QL08-1, (C, D) 23QL11-1, and (E, F) 23QL16-1.

(Figures 4A,C,E). Sillimanite occurs in two distinct forms: one as fibrous inclusions enclosed within garnet and cordierite in all three samples (Figures 4C,D,F), and the other as euhedral crystals distributed within the matrix (Samples 23QL11-1 and 23QL16-1; Figures 4D,F). Biotite is present either within the matrix (Figures 4A–C) or as relict flakes embedded in sillimanite + cordierite symplectites (Figures 4C–E). K-feldspar appears as coarse subhedral grains within the matrix in all three samples (Figures 4B,D,F), whereas plagioclase is limited in occurrence and may have formed through melt crystallization (Sample 23QL08-1; Figure 4B).

As discussed above, a distinctive decompression metamorphic reaction texture is recognizable. This is evident from the emergence of a cordierite rim encircling garnet or the formation of cordierite + sillimanite symplectites (Figures 4A,C,E). These features define the metamorphic history, which can be categorized into peak, post-peak, and retrograde phases. The peak metamorphic phase

exists without kyanite occurrence while including a g-bi-ksp-sill-liq-ilms-q mineral assemblage. During the post-peak phase, the rock displays g-pl-bi-ksp-sill-cd-liq-ilms-q assemblage. Consequently, the retrograde cooling phase is characterized by a sub-solidus assemblage, devoid of liquid.

5.2 Phase equilibria modelling

GeoPs v3.5.6.21170 software (Xiang and Connolly, 2022) was utilized for phase equilibria modelling, incorporating the ds62 thermodynamic dataset (Holland and Powell, 2011). Simulations were conducted within the NCKFMASHTO system, which includes Na_2O , FeO , MgO , Al_2O_3 , CaO , K_2O , SiO_2 , TiO_2 , H_2O , and O ($\text{Fe}^{3+}/\text{Fe}_{\text{total}}$) as key components. Owing to its negligible concentration (<0.08 wt%; Supplementary Table S3), MnO was omitted from the modelling process. The total P_2O_5 content was

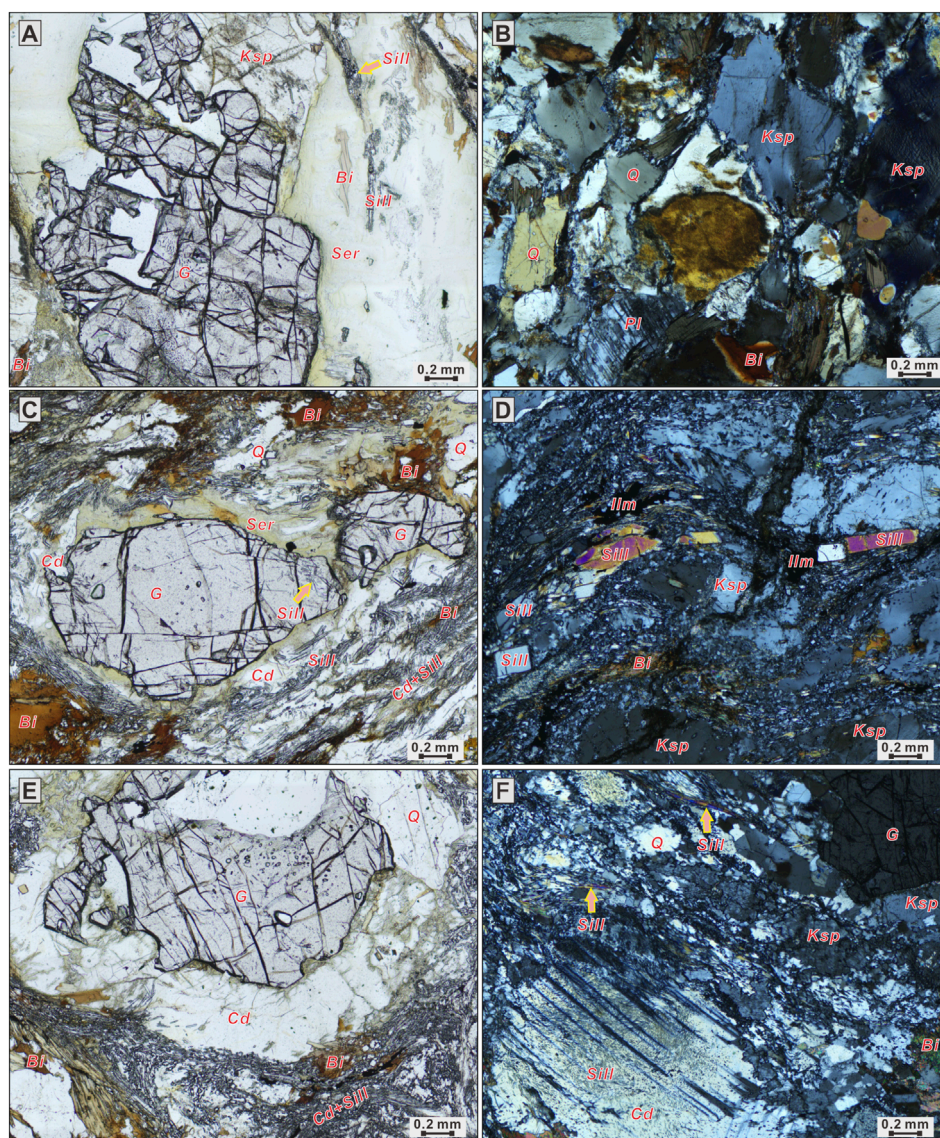


FIGURE 4

Photomicrographs showing key mineralogical assemblages and textural relationships in MP pelitic granulites: (A–B) 23QL08-1, (C–D) 23QL11-1, and (E–F) 23QL16-1. (A) Garnet porphyroblast enveloped by sericitized cordierite, enclosing sillimanite and biotite inclusions. (B) Matrix composed mainly of K-feldspar, biotite, and quartz, with minor plagioclase. (C) Garnet porphyroblast rimmed by symplectic intergrowths of cordierite and sillimanite. (D) Prismatic sillimanite occurs in the matrix. (E) Anhedral garnet porphyroblast encased by a cordierite corona and outer cordierite-sillimanite symplectites. (F) Fibrous sillimanite enclosed within cordierite.

assumed to be exclusively derived from apatite, necessitating a corresponding adjustment of the CaO content in the model. The appropriate H_2O and O (Fe^{3+}/Fe_{total}) contents were determined using the $T-M_{H_2O}$ diagram (Korhonen et al., 2013) and the potassium dichromate titration method, respectively. Due to the O (Fe^{3+}/Fe_{total}) value obtained for Sample 23QL11-1 using the titration method being excessively high, we adjusted our approach and adopted the $T-M_O$ diagram (Korhonen et al., 2013). The modelling incorporated activity-composition (a-x) models for plagioclase (Pl) and K-feldspar (Ksp) (Holland and Powell, 2003), together with garnet (G), silicate melt (Liq), muscovite (Mu), biotite (Bi), staurolite (St), cordierite (Cd), and orthopyroxene (Opx) (White et al., 2014). In addition, ilmenite

(Ilm) (White et al., 2014), spinel (Sp), and magnetite (Mt) (White et al., 2002) were incorporated into the model. Additionally, the following minerals were treated as pure phases: andalusite (And), rutile (Ru), kyanite (Ky), sillimanite (Sill), and quartz (Q). The whole-rock geochemical data obtained via XRF, along with the corresponding normalized molar ratios, are presented in Supplementary Table S3.

5.2.1 Sample 23QL08-1

To establish the optimal H_2O concentration for Sample 23QL08-1, $T-X_{H_2O}$ pseudosection analysis was performed at 5.5 kbar (Figure 5A), aligning with the retrograde pressure range of 4–6 kbar documented in previous research (Yin et al., 2014;

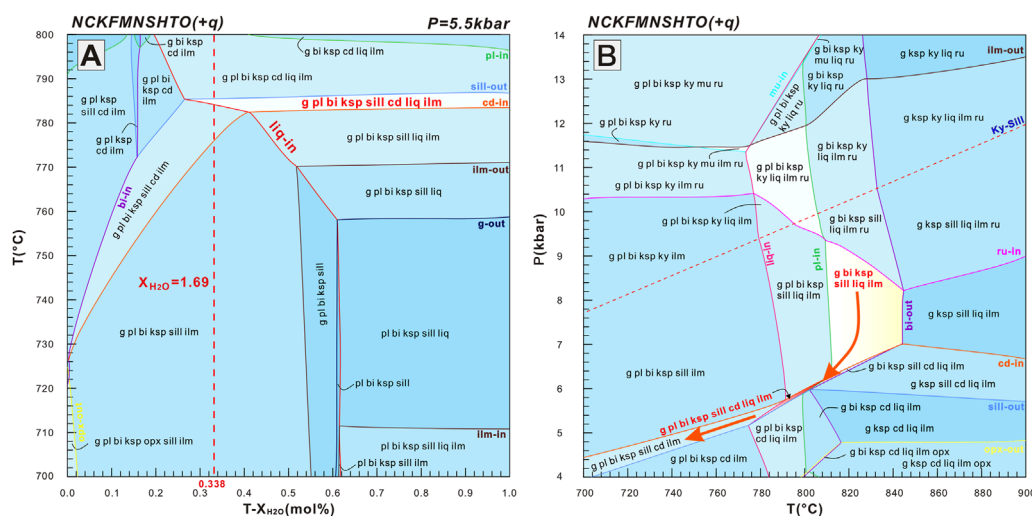


FIGURE 5
Phase equilibrium modelling results for 23QL08-1. (A) T- X_{H_2O} diagram computed at 5.5 kbar, with the red line indicating H_2O content used for P-T pseudosection. (B) P-T pseudosection illustrating the stability of fields of mineral assemblage and the proposed P-T trajectory.

Wu et al., 2020). For subsequent thermodynamic modelling, a value of 1.69 mol% H_2O was chosen based on the solidus midpoint of post-peak mineral assemblages (g-pl-bi-ksp-sill-cd-liq-ilm-q) (Figure 5A; Korhonen et al., 2013). Due to the restricted H_2O content, phase equilibrium modelling was conducted across 700°C–900°C and 4–14 kbar, taking into account an excess of quartz (Figure 5B). The solidus exhibits a sharp slope over a limited temperature interval of approximately 770°C–805°C. Similarly, the biotite-out curve follows a comparable trend but appears at temperatures 20°C–40°C higher. The rutile-in and cordierite-in curves both exhibit a positive correlation with pressure, occurring at pressures above ~8.2 kbar and below ~7.0 kbar, respectively.

The peak mineral assemblage of g-bi-ksp-sill-liq-ilm-q exists in a broad P-T field of 6.3–9.4 kbar and 810°C–844°C (Figure 5B). In contrast, the post-peak mineral assemblage of g-pl-bi-ksp-sill-cd-liq-ilm-q occurs within the restricted P-T conditions of 775°C–812°C and 5.2–6.3 kbar (Figure 5B). The development of sericitized cordierite encasing the garnet primarily indicates a transition from peak to post-peak stage, while the crystallization of plagioclase from melt marks the onset of the retrograde cooling phase (Figure 5B).

5.2.2 Sample 23QL11-1

For Sample 23QL11-1, an H_2O concentration of 1.42 mol%, representing the median position of the solidus within post-peak mineral assemblages, was adopted for subsequent thermodynamic simulations (Figure 6A). Based on the restricted H_2O content, phase equilibrium modelling was conducted across a P-T space spanning 700°C–900°C and 4–14 kbar, considering an excess of quartz (Figure 6B). The solidus exhibits a sharp slope, confined to a temperature window of approximately 778°C–845°C. The biotite-out curve appears above ~830°C. The rutile-in and cordierite-in

curves both exhibit a positive correlation with pressure, with rutile-in occurring at pressures above ~10.5 kbar and cordierite-in at pressures lower than ~6.4 kbar.

The peak metamorphic g-bi-ksp-sill-liq-ilm-q assemblage spans a broad P-T range of approximately 5.8–10.4 kbar and 780°C–832°C (Figure 6B). In contrast, the post-peak mineral assemblage of g-pl-bi-ksp-sill-cd-liq-ilm-q is well constrained within a much narrower P-T field, specifically 778°C–800°C and 4.9–5.8 kbar (Figure 6B). Similarly, the development of cordierite coronas or symplectitic assemblages comprising sillimanite and cordierite primarily signifies the shift from peak metamorphic conditions to the post-peak stage, with continued cooling transitioning into the retrograde cooling phase (Figure 6B).

5.2.3 Sample 23QL16-1

For Sample 23QL16-1, an H_2O concentration of 2.47 mol% was determined and used in the subsequent thermodynamic modelling (Figure 7A). Building on the determined H_2O content, phase equilibrium modelling was executed across 700°C–900°C and 4–14 kbar, assuming excess quartz (Figure 7B). The biotite-out curve appears above ~878°C. The rutile-in and cordierite-in curves both exhibit a positive correlation with pressure, occurring at pressures above ~9.8 kbar and below ~7.1 kbar, respectively.

The g-bi-ksp-sill-liq-ilm assemblage at peak metamorphism remains stable over a broad pressure–temperature interval, ranging from 6.6 to 10.6 kbar and 812°C–878°C (Figure 7B). In contrast, the post-peak mineral assemblage of g-pl-bi-ksp-sill-cd-liq-ilm-q is well constrained within a much narrower P-T field, specifically 785°C–825°C and 5.1–6.5 kbar (Figure 7B). The emergence of textural features dominated by cordierite, or symplectitic intergrowths comprised of sillimanite and cordierite delineates the transition from peak pressure metamorphism to post-peak decompression, while sustained cooling initiates the retrograde regime (Figure 7B).

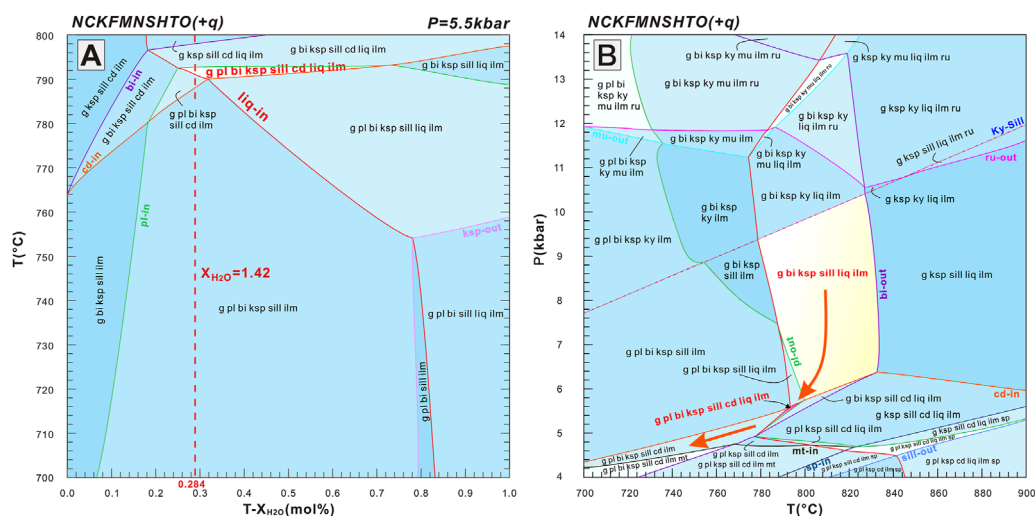


FIGURE 6
Phase equilibrium modelling results for 23QL11-1. (A) T- X_{H_2O} diagram modeled at 5.5 kbar, where the red line represents the chosen H_2O content for subsequent P-T pseudosection. (B) P-T pseudosection showing mineral assemblage stability fields and the proposed P-T trajectory.

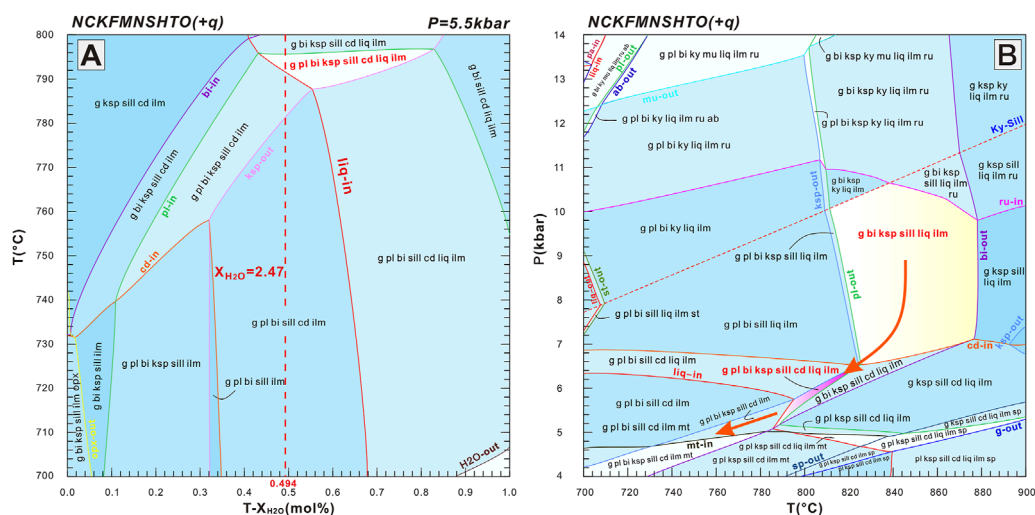


FIGURE 7
Phase equilibrium modelling results for 23QL16-1. (A) T- X_{H_2O} diagram computed at 5.5 kbar, with the red line illustrating the H_2O content used for subsequent P-T pseudosection. (B) P-T pseudosection depicting mineral assemblage stability fields and the proposed P-T evolution path.

5.3 Geochronology

5.3.1 U-Pb geochronology of zircon

Zircon crystals obtained from Sample 23QL08-1 exhibit either sub-rounded or stubby morphologies, typically measuring between 50 and 150 μm in size. Most of the grains in CL imaging exhibit well-defined core-rim textures (Figure 8A). The cores, displaying distinct bright oscillatory zoning, are considered relics of detrital sources, while the structureless overgrowth rims and the individual grains with chaotic zoning are regarded as metamorphic in origin. The zircon core analysis yielded nine datasets and two spots (29 and 24), which delivered concordant results showing $^{207}Pb/^{206}Pb$ ages at 2011 ± 89 Ma and 2021 ± 45 Ma (Figure 9A). High

Th/U ratios (0.53–0.54) observed in these analyses indicate an igneous origin for zircon (Supplementary Table S1; Figure 9A). These results indicate the crystallization age of MP pelitic granulite protoliths. Additionally, the upper intercept age analysis based on twenty-one analytical measurements targeting zircon rims and discrete metamorphic zircons yielded a result of 1943 ± 18 Ma ($n = 21$; $MSWD = 2.6$; Figure 9A), and Th/U ratios were 0.00–0.23 (Supplementary Table S1). The geochronological results are considered to represent the metamorphic age of the MP pelitic granulites.

Zircon crystals from Sample 23QL11-1 exhibit dimensions predominantly between 40 and 100 μm , with most grains showing irregular to moderately rounded shapes (Figure 8B). CL analysis

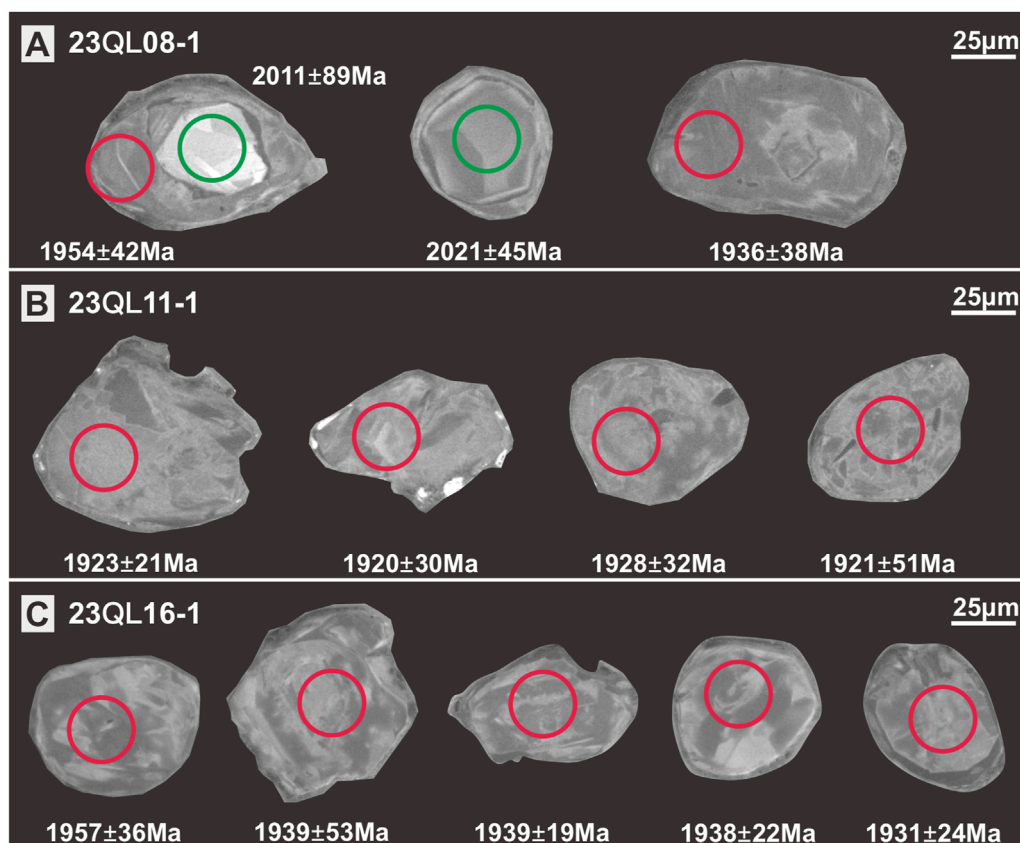


FIGURE 8

CL images of representative zircon grains from (A) 23QL08-1, (B) 23QL11-1, and (C) 23QL16-1. Green and red circles indicate analytical spots at core and rim positions, respectively, with their corresponding $^{207}\text{Pb}/^{206}\text{Pb}$ ages labeled.

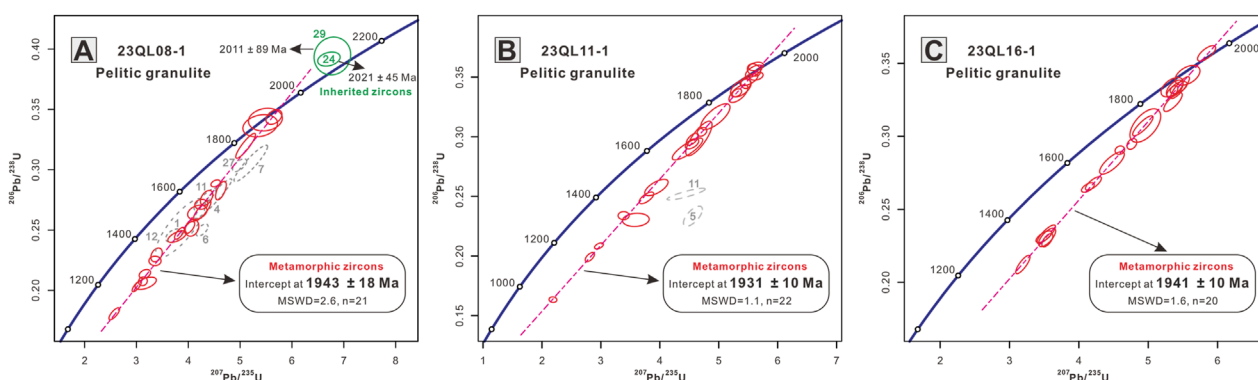


FIGURE 9

Zircon U-Pb concordia plots for (A) 23QL08-1, (B) 23QL11-1, and (C) 23QL16-1.

reveals that a significant proportion of these grains contain weakly sector-zoned or chaotic internal textures (Figure 8B), consistent with characteristics of metamorphic zircons. Twenty-four available analyses were performed on these metamorphic zircons, with two excluded attributed to variable Pb loss (Supplementary Table S1; Figure 9B). The remaining data define an intercept age of 1931 ± 10 Ma ($n = 22$, $\text{MSWD} = 1.1$; Figure 9B), indicating the age of metamorphism.

Zircons isolated from Sample 23QL16-1 generally measure between 50 and 100 μm in maximum dimension and primarily exhibit equant to subrounded or angular grain shapes (Figure 8C). CL images of these zircons demonstrate that the majority display faintly sector-zoned or disordered internal textures (Figure 8C), aligning with features typically associated with metamorphic origin. Twenty analytical datasets were acquired from these metamorphic zircon grains, which exhibited characteristically low Th/U ratios

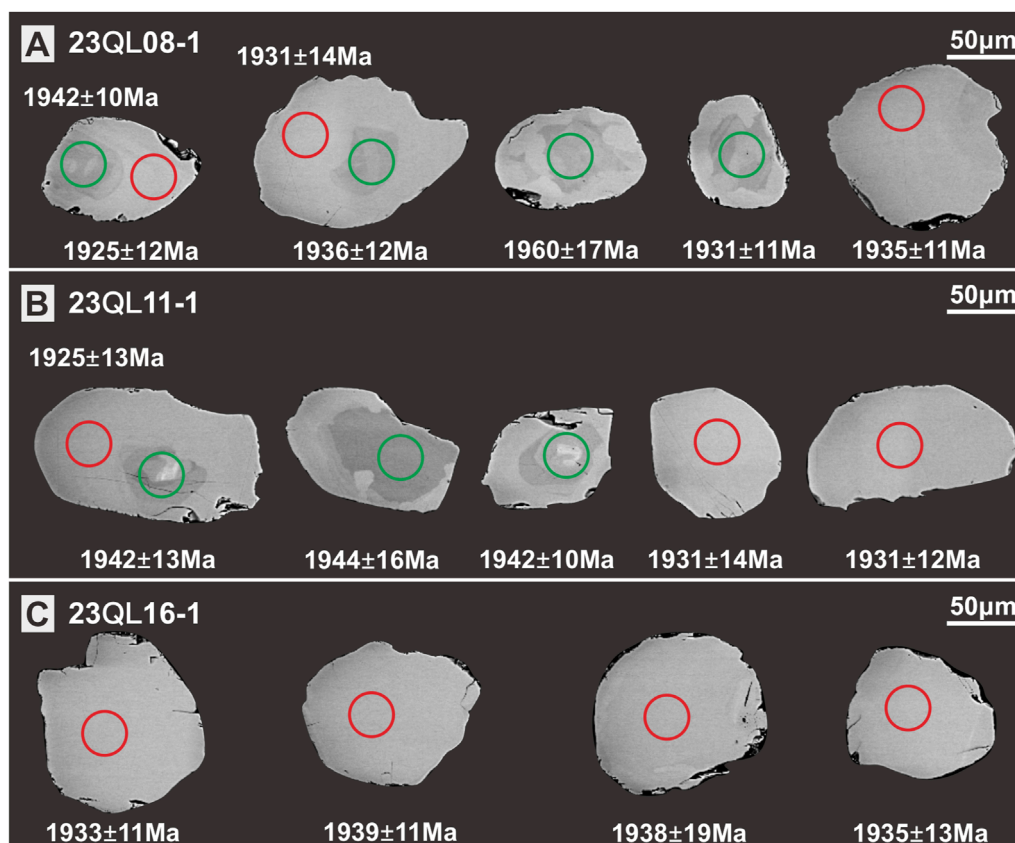


FIGURE 10
BSE images of representative monazite grains from (A) 23QL08-1, (B) 23QL11-1, and (C) 23QL16-1. Analytical spots at core and rim positions are marked by green and red circles, respectively, with associated $^{207}\text{Pb}/^{206}\text{Pb}$ ages labeled.

of 0.00–0.11 (Supplementary Table S1). The analyzed data pointed to a metamorphic event that occurred at 1941 ± 10 Ma ($n = 20$, MSWD = 1.6; Figure 9C) based on an upper intercept age.

5.3.2 U-Pb geochronology of monazite

Monazite crystals extracted from Sample 23QL08-1 exhibit subrounded to equant morphologies, with diameters of 100–200 μm (Figure 10A). BSE imaging reveals their overall homogeneity, though some grains exhibit distinct core-rim structures (Figure 10A). The weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age from nineteen out of twenty-four spot analyses targeting homogeneous domains and lower-luminescence rims came out to be 1931 ± 3 Ma (MSWD = 0.46, $n = 19$; Figure 11A). Two analyses of core domains produced concordant ages of 1960 ± 17 Ma and 1942 ± 10 Ma (Figure 11A), whereas three remaining core-focused analyses generated a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1935 ± 6 Ma (MSWD = 0.32; $n = 3$; Figure 11A). Since the cores and rim ages fall within analytical uncertainty, the combined data yielded a final weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1932 ± 3 Ma (MSWD = 0.66; $n = 23$; Figure 11B), which is taken to represent the monazite formation age and the corresponding metamorphic event. Chondrite-normalized REE patterns of monazite are characterized by strong LREE enrichment, a pronounced negative Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.01\text{--}0.39$), and

depleted HREE contents, resulting in a right-inclined pattern ($\text{La}_\text{N}/\text{Yb}_\text{N} = 327\text{--}10995$; Figure 12A).

Monazite crystals from Sample 23QL11-1 are subrounded and 100–200 μm in diameter (Figure 10B). BSE imaging reveals predominantly homogeneous textures, though some grains display concentric zonation indicative of core-rim structures (Figure 10B). The weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age from twenty out of twenty-eight spot analyses of targeting homogeneous domains and low-luminescence rims came out to be 1936 ± 3 Ma (MSWD = 0.50, $n = 20$; Figure 11C). Eight core-focused analyses yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1939 ± 5 Ma (MSWD = 0.65; $n = 8$; Figure 11C). However, given the overlap within analytical uncertainty, no statistically significant distinction exists between core and rim ages. Consequently, a composite weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1935 ± 3 Ma (MSWD = 0.69; $n = 28$; Figure 11D) is considered representative of monazite crystallization during metamorphic events. Monazite from sample 23QL11-1 exhibits a right-inclined REE pattern ($\text{La}_\text{N}/\text{Yb}_\text{N} = 316\text{--}12520$), characterized by strong enrichment in LREE and significant depletion in HREE (Figure 12B), along with a pronounced negative Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.02\text{--}0.35$).

Monazite crystals from Sample 23QL16-1 are subrounded to equant, with diameters spanning 100–150 μm . Moreover, BSE

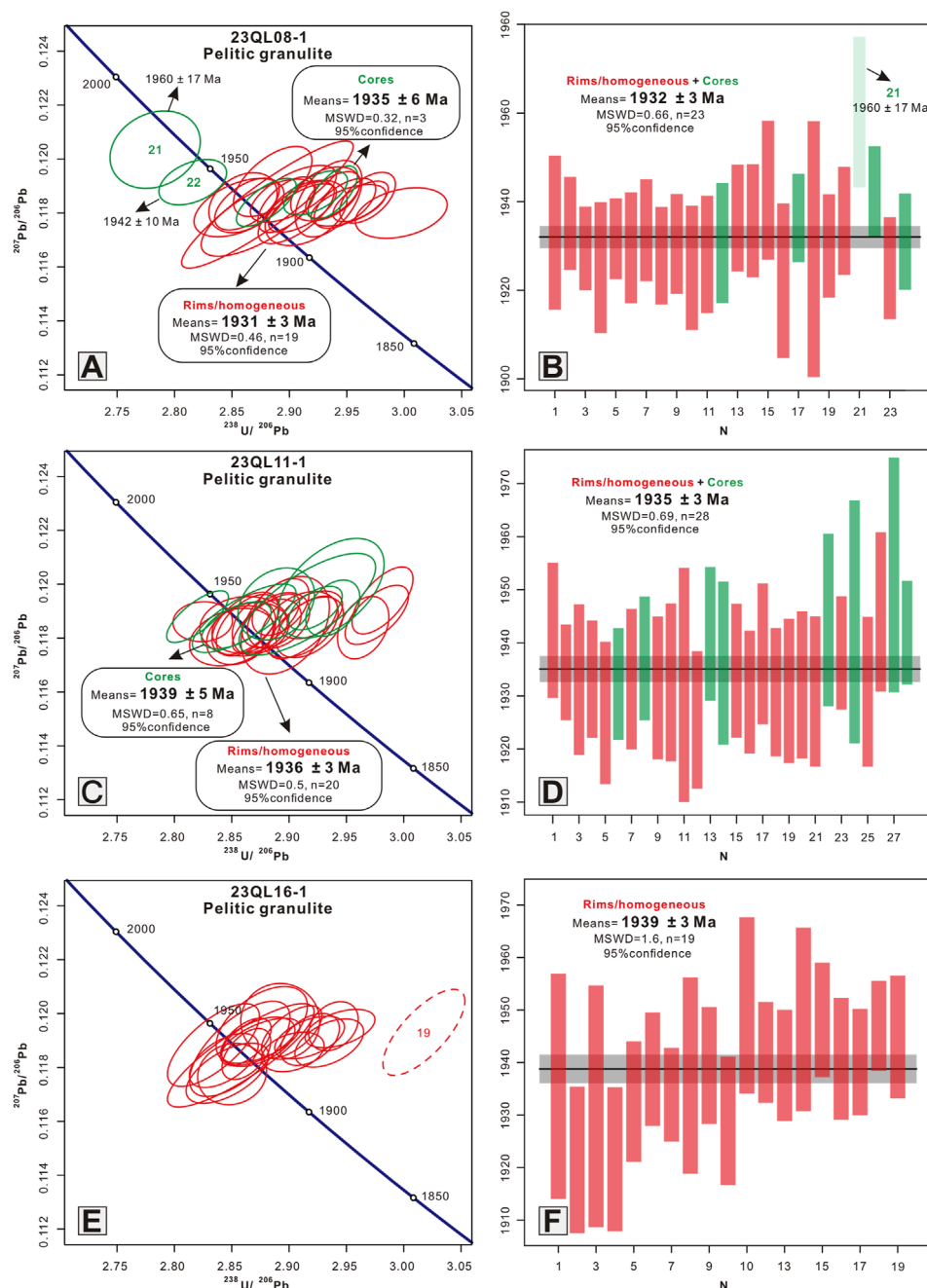


FIGURE 11
Monazite U-Pb Tera-Wasserburg diagrams and bar charts for (A, B) 23QL08-1, (C, D) 23QL11-1, and (E, F) 23QL16-1.

images indicate that most grains exhibit a predominantly uniform texture (Figure 10C). A total of 20 monazite analyses were conducted, with one analysis (spot 19) displaying discordance, probably owing to Pb loss. Nineteen additional analyses yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1939 ± 3 Ma (MSWD = 1.6; n = 19; Figures 11E,F), which is considered to reflect the metamorphic event. Monazite from sample 23QL16-1 also shows a right-inclined REE pattern ($\text{La}_N/\text{Yb}_N = 335\text{--}7,232$) with strong LREE enrichment, HREE depletion, and a pronounced negative Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.03\text{--}0.36$; Figure 12C).

6 Discussion

6.1 Metamorphic P-T path

Through the integration of petrography, geochronology and phase equilibrium modelling, the MP pelitic granulites of the Qianlishan Complex underwent three different metamorphic stages. Without mineral chemistry data, the peak mineral assemblage of g-bi-ksp-sill-liq-ilm-q remains broadly defined, with its constraints primarily controlled by the pl-out line, ky-sill transformation line,

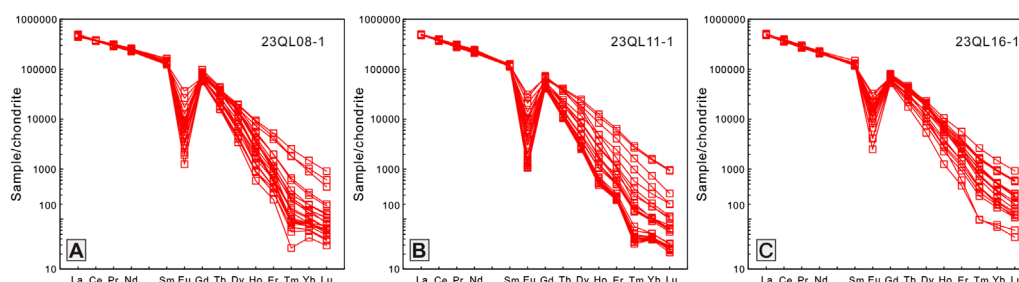


FIGURE 12
REE patterns of monazite from (A) 23QL08-1, (B) 23QL11-1, and (C) 23QL16-1, normalized to chondrite values. Chondrite reference values are taken from Sun and McDonough (1989).

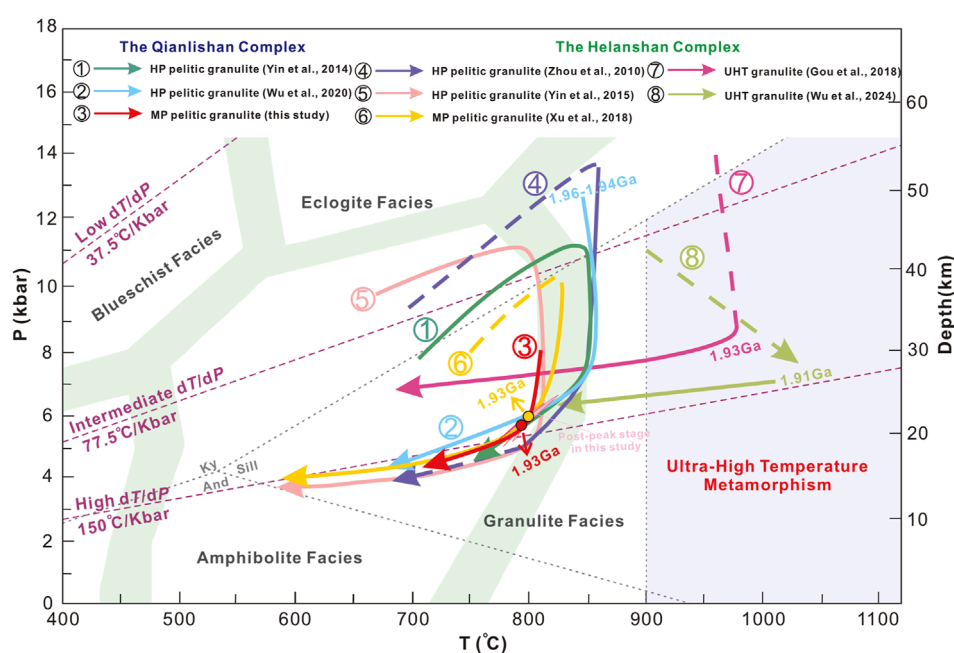


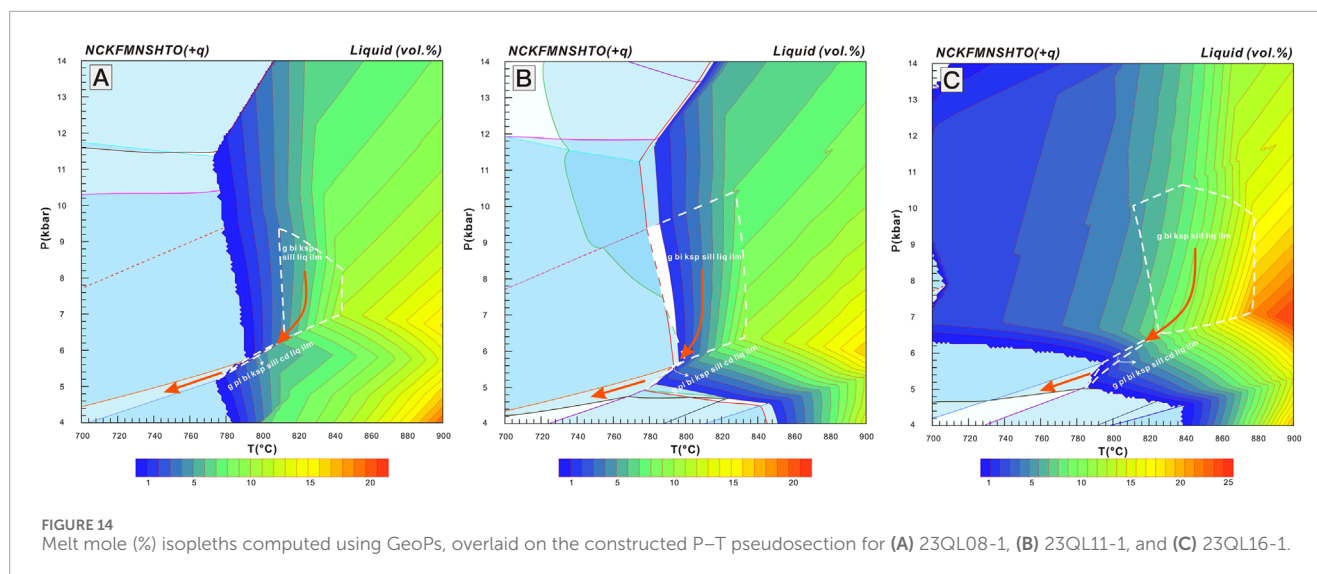
FIGURE 13
Comparative P-T trajectories for HP, MP, and UHT pelitic granulites within the Qianlishan-Helanshan Complex, located in the western Khondalite Belt. Metamorphic facies boundaries follow the classification by Brown and Johnson (2018).

ru-in line, and bi-out line. Following peak metamorphism, cordierite develops at the expense of garnet, while plagioclase crystallizes from the melt. The post-peak mineralogical assemblage is located in the very narrow field (g-pl-bi-ksp-sill-cd-liq-ilm-q), which defines well-constrained P-T conditions (775°C – 825°C /4.9–6.5 kbar) of the post-peak stage. All MP granulites experience metamorphic evolution that follows a single clockwise P-T trajectory, transitioning from peak pressure conditions through post-peak evolution to sub-solidus cooling. An initial phase of nearly isothermal decompression, succeeded by near-isobaric cooling, characterizes the P-T paths (Figures 5–7). Subsequently, we analyzed these P-T paths in relation to previously reported HP, MP, UHT pelitic/felsic granulites within the Qianlishan-Helanshan Complexes of the western Khondalite Belt (Figure 13), which share similar clockwise P-T trajectories but differ in their peak pressure conditions

(Zhou et al., 2010; Yin et al., 2014; Yin et al., 2015; Xu et al., 2018; Gou et al., 2018; Wu et al., 2020; Wu et al., 2024). Furthermore, our results are comparable to those documented for MP pelitic granulites in the central segment (Daqingshan-Wulashan Complex; Cai et al., 2014; Cai et al., 2017) and the eastern segment (Jining Complex; Jiao et al., 2013) of the Khondalite Belt. This suggests that they may have undergone the same coherent orogenic event (Spear, 1993), despite being buried at different depths.

6.2 Age interpretation and tectonic significance

U-Pb dating via LA-ICP-MS on three MP pelitic granulites produced zircon upper intercept ages of 1943 ± 18 Ma, $1931 \pm$



10 Ma, and 1941 ± 10 Ma (Figure 9), while monazite from the same samples yielded weighted mean U–Pb ages of 1932 ± 3 Ma, 1935 ± 3 Ma, and 1939 ± 3 Ma (Figure 11). It seems that zircon ages appear to be slightly older than monazite ages within the same rock (Figures 9, 11), likely due to differences in the temperatures at which zircon and monazite grow (Kelsey et al., 2008). However, both age populations converge on a metamorphic timing of ~ 1.93 Ga within the uncertainty. The obtained age is slightly younger than the metamorphic zircon ages (1.96–1.94 Ga) identified in HP pelitic and felsic granulites (Yin et al., 2009; Qiao et al., 2016; Wu et al., 2020), which were linked to the HP metamorphic phase. The ~ 1.93 Ga age also corresponds with a ~ 1.92 Ga metamorphic population in g-sill-bi-pl gneiss from the Qianlishan Complex (Yin et al., 2009), as well as similar ages in MP granulites from the Helanshan Complex (Xu et al., 2018).

The ~ 1.93 Ga age identified in MP granulites from the Helanshan Complex has been interpreted as marking the onset of nearly isobaric cooling (Xu et al., 2018). Experimental petrology and phase modelling support this interpretation, which shows that zircon dissolves during heating but crystallizes during melt solidification in the cooling phase (Kelsey and Powell, 2011; Zhang et al., 2013; Lu et al., 2022). Monazite exhibits a similar behavior (Yakymchuk and Brown, 2014). Monazite grains from three MP pelitic granulites all exhibit significant negative Eu anomalies (Figure 12), likely reflecting enhanced feldspar crystallization at the retrograde cooling phase (Wang et al., 2017; Lu et al., 2022). Pseudosection analysis indicates that as metamorphism progresses from peak pressure conditions toward the post-peak and cooling phases, melt crystallization becomes dominant (Figure 14), accompanied by the initiation of plagioclase formation (Figures 5–7). Based on this interpretation, the older monazite ages of 1960 ± 17 Ma and 1942 ± 10 Ma (Figures 11A,B) may have been preserved as inclusions within large, intact minerals, preventing it from dissolution (Baldwin et al., 2006; Jiao et al., 2020) and potentially representing the peak metamorphic age. However, the majority of monazite grains, with ages clustered around 1.93 Ga, may correspond to the initiation of the cooling phase or retrograde

metamorphic processes following granulite-facies conditions in the Qianlishan Complex.

Integrating prior geochronological data and P–T trajectory results (Figure 13), we can deduce that the peak-pressure metamorphism of pelitic granulites in the Qianlishan Complex happened between 1.96 and 1.94 Ga before experiencing decompression and retrograde cooling around 1.93 Ga. This further supports that the Khondalite Belt underwent a continent–continent collision around ca. 1.95 Ga (Yin et al., 2009; Yin et al., 2011), which was shortly followed by a shallow slab-breakoff event (e.g., Gou et al., 2019; Yin et al., 2023). This process triggered the uplift of pelitic granulites in the western Khondalite belt to mid-crustal levels, culminating in their subsequent cooling around 1.93 Ga (Xu et al., 2018).

7 Conclusion

- (1) The Qianlishan MP pelitic granulites experienced metamorphic processes along a clockwise P–T trajectory, starting from near-isothermal decompression and transitioning into near-isobaric cooling.
- (2) U–Pb geochronology applied to zircon and monazite yielded a metamorphic age of ~ 1.93 Ga, suggesting the initiation of the retrograde cooling phase.
- (3) The peak-pressure metamorphism of pelitic granulites in the Qianlishan Complex occurred at ~ 1.95 Ga, followed by decompression and retrograde cooling around 1.93 Ga.

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 authors.

Author contributions

SW: Writing – review and editing, Investigation, Funding acquisition, Conceptualization, Supervision, Writing – original draft, Validation, Data curation, Visualization, Methodology. YS: Methodology, Writing – review and editing, Validation, Data curation, Formal Analysis. QW: Formal Analysis, Writing – review and editing, Data curation, Validation, Methodology. HQ: Funding acquisition, Writing – review and editing, Investigation, Validation, Supervision, Data curation, Methodology, Visualization.

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Supplementary material

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