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Letter

When did the Chicheng eclogite form? Revisiting the Paleoproterozoic-late Paleozoic controversy via zircon inclusion and U-Pb dating

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ABSTRACT

Since its discovery in 2002, the tectonic significance of the Chicheng eclogite along the northern margin of the North China Craton (NCC) has been debated, with conflicting interpretations regarding its peak metamorphic age (Paleoproterozoic vs. Late Paleozoic). This controversy arises from unclear correlations between isotopic ages and metamorphic mineral assemblages. Here, we resolve this issue by integrating mineral inclusion analysis with zircon textural characteristics to constrain metamorphic generations of zircons. Systematic investigations of two eclogite samples (CC26 and CC28) reveal three distinct indicator mineral assemblages preserved in zircon domains: (1) eclogite-facies indicators (omphacite, kyanite and rutile); (2) non-eclogite-facies indicators (plagioclase, diopside, orthopyroxene, amphibole and ilmenite); and (3) persistent phases (garnet and quartz). LA-ICPMS U-Pb geochronology delineates three metamorphic stages: (1) peak eclogite-facies metamorphism at 334–339 Ma recorded in eclogite-facies indicators bearing zircon domains or metamorphic cores; (2) prograde metamorphism at 357–361 Ma preserved in a few zircon cores or the domains with non-eclogite-facies indicators; and (3) retrograde stage at 320–316 Ma recorded in zircon rims, respectively. Notably, scattered ages of 283–304 Ma likely reflect post-collisional magmatic thermal events. The Hongqiyingzi Complex (hosting the Chicheng eclogite) exhibits contrasting lithological and tectono-thermal records compared to the NCC's Dantazi Complex. These findings support a Late Paleozoic origin for the Chicheng eclogite, related to orogenic processes of the Central Asian Orogenic Belt (CAOB), rather than Paleoproterozoic NCC amalgamation events.

1. Introduction

As key petrological indicators of convergent plate boundaries, eclogites and their formation conditions and timing are of great importance for reconstructing ancient plate tectonic histories. The Chicheng eclogite along the northern margin of the NCC has generated substantial interest with the geological community since its initial discovery in 2002 (Ni, 2002; Ni et al., 2004, 2006). Nevertheless, considerable controversy persists regarding its tectonic significance, primarily centered on two contrasting interpretations: (1) some studies attribute the eclogite formation to Late Paleozoic subduction-collision processes of the CAOB (Chu et al., 2013; Ni, 2002; Ni et al., 2004, 2006; Wang et al., 2012; Yan et al., 2025); (2) conversely, other studies proposed a Paleoproterozoic origin associated with NCC amalgamation under modern plate tectonic regimes (Liu et al., 2019; Wang et al., 2002; Wei et al., 2023, 2024; Zhang et al., 2016a, 2020).

This fundamental divergence arises from conflicting interpretations of peak metamorphic ages, the Late Paleozoic (~325 Ma) vs. Paleoproterozoic (~1900 Ma), although extensive geochronological investigations have been conducted on the eclogites (Chu et al., 2013; Kong et al., 2011; Li et al., 2022; Ni et al., 2004, 2006; Wang, 2010; Yan et al., 2025; Zhang et al., 2016a, 2020; Zou et al., 2021). While the region's polyphase tectono-metamorphic evolution (Chu et al., 2013; Liu et al., 2007; Wang, 2010; Wang et al., 2012; Wei et al., 2024; Zhang et al., 2016a) may contribute to these discrepancies, the core issue lies in absence of reliable links between metamorphic ages and mineral assemblages in the Chicheng eclogite.

To resolve this controversy, we conducted detailed mineral inclusions analyses to reveal petrogenesis of the host zircons, enabling reliable interpretation of U-Pb age data within precise metamorphic contexts. Significantly, eclogite-facies indicator minerals were identified for the first time within specific zircon domains, establishing direct constraints on peak metamorphic timing. Our findings demonstrate that the Chicheng eclogite was formed at the Late Paleozoic, rather than the Paleoproterozoic.

2. Geological settings

The Chicheng eclogite, situated along the northern margin of the NCC (Fig. 1a), constitutes a lithological component of the Hongqiyingzi Complex. This Complex exhibits an *E*-W strike, demarcated to the south by the Chicheng-Chongli shear zone (Fig. 1b). In the Chicheng area, the Hongqiyingzi Complex mainly comprises granitic orthogneisses, metasedimentary rocks (dominantly garnet-bearing biotite plagioclase gneisses with subordinate graphite-bearing gneisses and marbles), eclogites and serpentinized peridotites (e.g., Chu et al., 2013; Liu and Zhang, 2019; Lu et al., 2009; Ni et al., 2004, 2006; Wang, 2010; Wang et al., 2012). Recently, a few studies interpreted these units as components of a Paleoproterozoic ophiolitic mélange (termed the Chicheng mélange) (Liu and Zhang, 2019; Wang et al., 2002; Wei et al., 2024; Zhang et al., 2016a, 2020). In contrast, the Dantazi Complex, located south side of the Chicheng-Chongli shear zone, is characterized by Neoarchean tonalite-trondhjemite-granodiorite (TTG) gneisses with some mafic and pelitic high-pressure granulites or amphibolites (e.g.,

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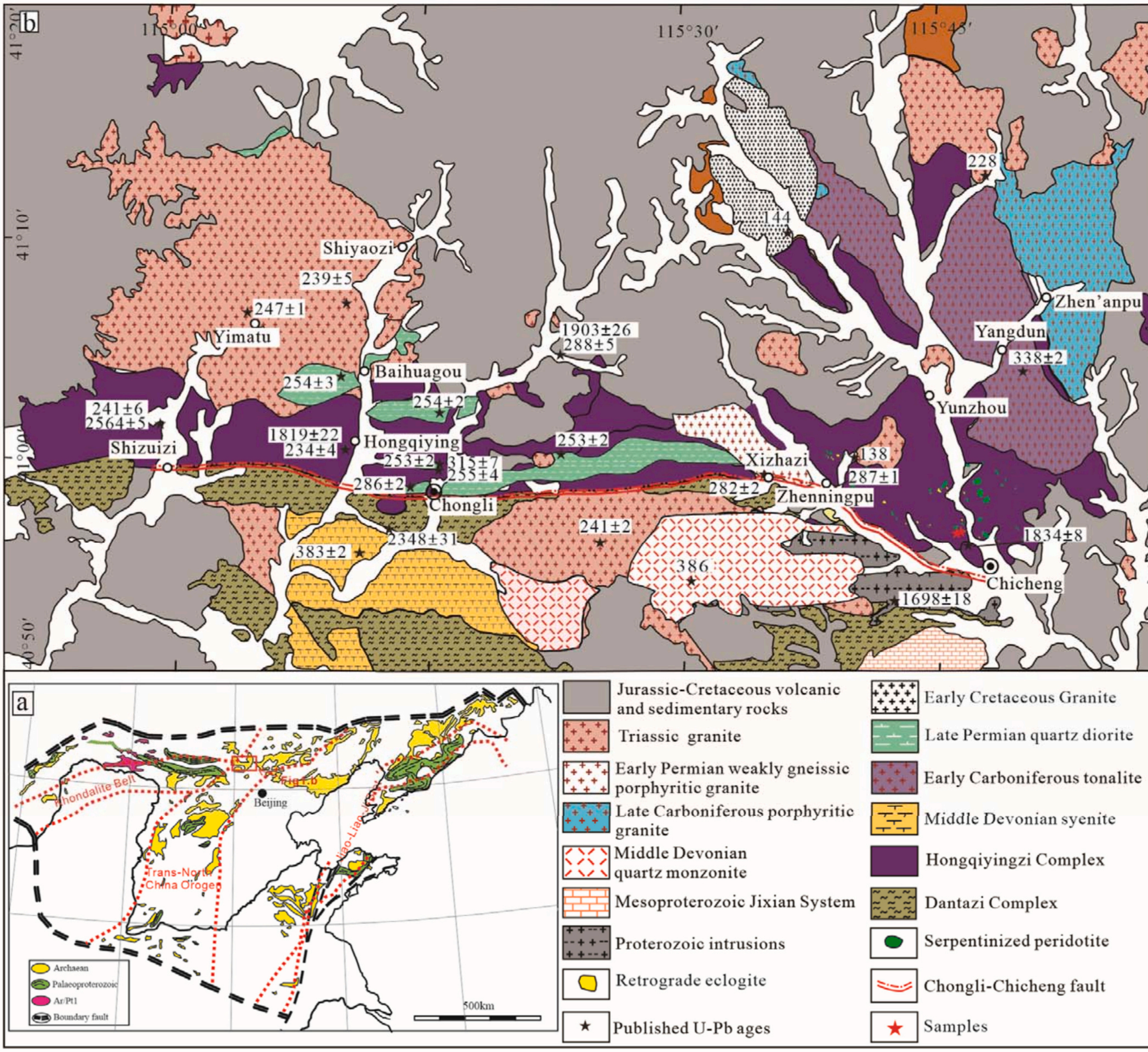

Fig. 1. (a) Early Precambrian metamorphic basements and Paleoproterozoic mobile belts in the North China Craton (Zhai and Liu, 2003). Dashed red lines represent the boundary of three different continental collisonal orogenic belts by Zhao et al. (2005). (b) Geological map of the Chongli– Chicheng area, northern Hebei Province, Modified after Wang et al. (2011) and Wang et al. (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Liu et al., 2007; Zhang et al., 2016b, 2021).

The Hongqiyingzi Complex preserves a polyphases tectono-metamorphic history spanning from Neoarchean to Mesozoic, encompassing: the Neoarchean and Paleoproterozoic cratonization of the NCC, as well as the Phanerozoic overprinting from the CAOB orogenesis and Mesozoic Yanshanian tectonic movement (e.g., Chu et al., 2013; Liu et al., 2007; Wang, 2010; Wang et al., 2012; Wei et al., 2024; Zhang et al., 2016a). Zircon U-Pb ages reveal two prominent metamorphic age clusters: 1950–1800 Ma and ~ 360–280 Ma (e.g., Chu et al., 2013; Liu et al., 2007; Zhang et al., 2016a, 2020), and several episodic magmatic pulses at ~2500 Ma, 1850–1800 Ma, 1750–1680 Ma, ~390 Ma, 324–276 Ma, 250–220 Ma and ~ 140 Ma (e.g., Liu et al., 2007, 2010; Wang et al., 2009, 2012, 2017; Wang, 2010; Zhang et al., 2007a, 2007b, 2007c, 2009). Structurally, the Complex displays progressively north- to northeast-dipping foliations approaching the Chicheng-Chongli shear zone. It is consistent with regional structural features, showing a series of north-dipping thrust system expanded towards the craton interior, which is interpreted as part of the CAOB-related thrust belt along the NCC northern margin (Zhang et al., 2014). These thrusts truncate Late Carboniferous-Permian granites, and are unconformably overlain by Jurassic-Cretaceous volcanic-sedimentary sequences. Subsequent Yanshanian thrust faults generated oppositely vergent thrust faults, demonstrating polyphase reactivation (Wang et al., 2013; Zhang et al., 2014).

3. Field occurrence and petrology

The Chicheng eclogites predominantly occur in the northern sector of Chicheng county (Fig. 1b), occurring as lenses or blocks within garnet-bearing biotite-plagioclase gneisses. These eclogite lenses, ranging from several centimeters to tens meters, demonstrate structural concordance with their host rock foliations. Notably, spatial associations with serpentinized peridotites are observed in localized domains.

Hand specimen analysis reveals extensive and intensive retrogression in most eclogites, with primary eclogite-facies mineralogy largely replaced by amphibolite-facies assemblages (garnet + clinopyroxene + amphibole + plagioclase; Fig. 2). Preservation of diagnostic high-pressure parageneses is limited to weakly retrograded samples, where symplectitic plagioclase-diopside intergrowths pseudomorph precursor Na-rich clinopyroxene. To constrain the metamorphic chronology, two representative samples were selected: CC26 (weakly retrogressed) and CC28 (intensely retrogressed).

Sample CC26 comprises garnet (25 %–30 %), omphacite pseudomorphs (45 %–50 %; diopside-plagioclase±orthopyroxene symplectites), amphibole (15 %–20 %), and minor quartz (~3 %) (Fig. 2a). Diagnostic eclogite-facies indicators, omphacite and kyanite are exclusively preserved as inclusions within garnet mantles to rims (Fig. 2b). Amphibole, plagioclase, diopside, epidote and accessary rutile, ilmenite and titanite are preserved in some garnet cores. Amphibole has two habits in matrix, either as symplectitic intergrowths with plagioclase surrounding garnet, or as irregular grains replacing diopside, which suggest that the amphibole is retrograde. The reconstructed peak mineral assemblage possibly consists of garnet + omphacite + kyanite + rutile + quartz.

Sample CC28 is intensively retrograded and dominated by amphibole (55 %–60 %), with subordinate garnet (15 %–20 %), plagioclase (10 %–15 %), quartz (5–8 %) and diopside (~3 %) (Fig. 2c). Although, no omphacite was detected, relic textures of amphibole-plagioclase-diopside symplectites locally attest to precursor omphacite (Fig. 2d).

Integrating petrological evidence, three distinct metamorphic stages are identified: prograde (M_1), peak (M_2) and retrograde (M_3) stages. The M_1 includes mineral inclusions that are protected in garnet cores and mantles, namely plagioclase + amphibole + diopside + epidote + titanite + ilmenite + garnet, representing pre-eclogite-facies amphibolite-facies assemblage. The M_2 stage is defined by garnet mantles to rims and the inclusions, consisting of garnet + omphacite + kyanite + rutile + quartz, representing eclogite-facies assemblages (indicating peak pressures >1.6 GPa). The minerals of M_3 stage include symplecitic diopside + plagioclase + minor orthopyroxene + amphibole + ilmenite, representing decompression granulite- to amphibolite-facies assemblages. The results are similar with previous studies (Ni et al., 2004, 2006; Zhang et al., 2020). A comprehensive analysis of metamorphic petrology and P-T paths of the studied eclogites will be presented in a forthcoming publication.

4. Results

4.1. Mineral inclusions in zircons

Many mineral inclusions were identified for the first time in zircon grains from the Chicheng eclogite in this study. They were divided into three distinct mineral assemblages: (1) eclogite-facies indicators, including omphacite, kyanite and rutile; (2) non-eclogite-facies indicators, diopside, amphibole, plagioclase, orthopyroxene and ilmenite, which could be formed either during prograde or retrograde stages; and (3) persistent minerals, including garnet and quartz, which could be stable (sometimes metastable) under prograde, peak and retrograde metamorphic stages.

Analytical methods are presented in the Appendix 1, with representative mineral inclusion composition provided in Appendix 2 (Table S1).

In sample CC26, eclogite-facies indicators were detected in some zircon grains, including omphacite, rutile and kyanite (Fig. 3a). Two omphacite grains have Na_2O content of 2.73 and 3.48 wt%, with Jd

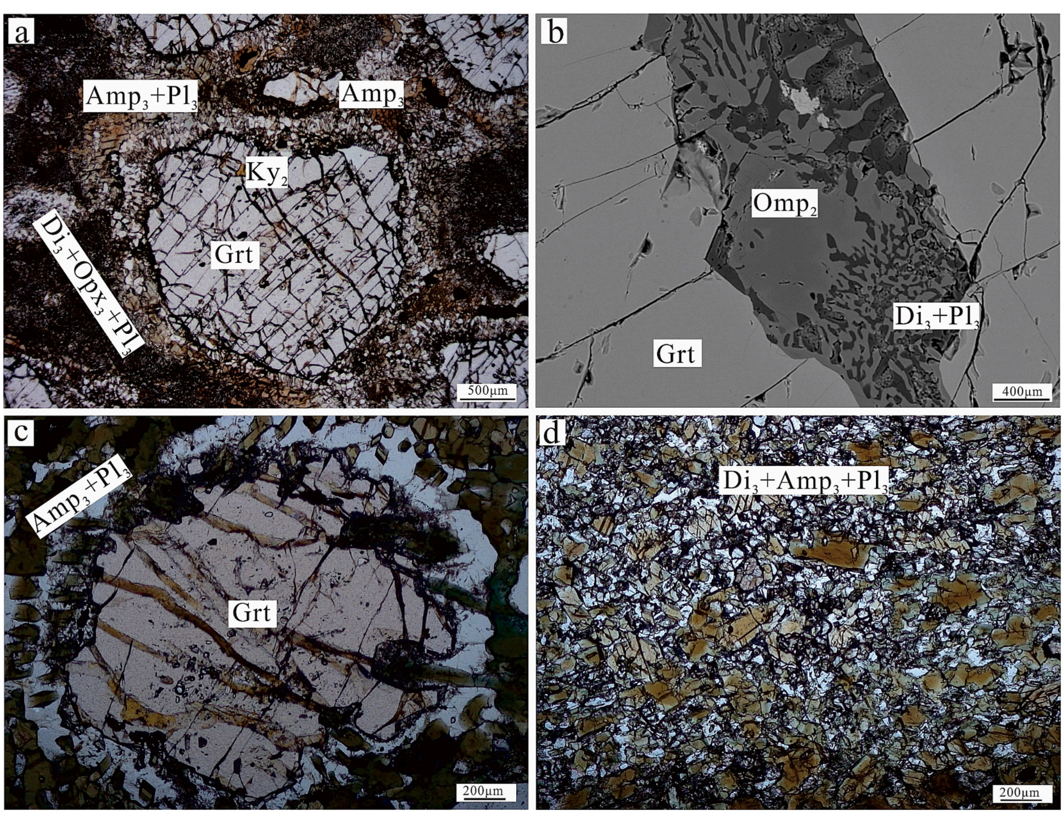

Fig. 2. Representative photomicrographs of the retrograde eclogites from the Chicheng area. (a) The Amp_3 + Pl_3 corona around garnet and Ky_2 inclusion, omphacite pseudomorphs (symplectitic intergrowth of Di_3 + Pl_3 + Opx_3) (CC26); (b) Omp_2 included in garnet, and was partially replaced by Di_3 + Pl_3 (CC26); (c) The Amp_3 + Pl_3 corona around garnet (CC28); (d) Recrystallized symplectitic intergrowth of Amp_3 + Pl_3 + Di_3 (CC28).

content of 21 and 26 mol%. Non-eclogite-facies indicators including diopside, orthopyroxene, amphibole and ilmenite were identified in several grains (Fig. 3a). Diopside has low Na_2O content (<1.0 wt%), with Jd content of ~5.0 mol%. Orthopyroxene is hypersthene with Mg# of 0.68. Amphibole is magnesio-hornblende with Mg# of 0.87. As persistent minerals, quartz grains were identified in some zircon domains (Fig. 3a), and only one garnet (maybe metastable) is observed in the grey-dark zircon rim with composition of Alm_{52} Py_{30} Grs_{16} Sps_2.

In sample CC28, only one rutile inclusion within a grey-white zircon represents the relic of eclogite-facies (Fig. 3b). A few andesine plagioclase ($An_{38–47}$) grains as non-eclogite-facies indicators were recognized in dark zircon rims (Fig. 3b). Garnet grains with composition of $Alm_{59–64}$ $Py_{9–17}$ $Grs_{20–22}$ $Sps_{3–7}$ were mainly identified in zircon cores, with one exception in dark grey rim (Fig. 3b).

4.2. Zircon U-Pb ages and trace elements

4.2.1. Sample CC26

Zircon grains from sample CC26 exhibit subrounded to anhedral morphologies, with diameter ranging from 80 to 120 um. They display low luminescence and structureless in CL images (Fig. 3a). Thirty-six spots were analyzed on 34 grains. The isotope data and trace elements are listed in Appendix 2 (Table S2). Based on inclusion assemblages and U-Pb ages, these zircon analyses were classified into four distinct groups (Fig. 4a). For Group 1, eclogite-facies indicator minerals were detected. Ten analyses yield apparent $^{206}Pb/^{238}U$ ages of 331–349 Ma, with a lower intercept age of 344 ± 19 Ma and a $^{206}Pb/^{238}U$ weighted average age of 339 ± 7 Ma (Fig. 4b). For Group 2, non-eclogite-facies indicators were identified, and four analyses yield a lower intercept age of 361 ± 15 Ma and a $^{206}Pb/^{238}U$ weighted mean age of 361 ± 15 Ma (Fig. 4c). For Group 3, non-eclogite-facies indicators were detected, and fourteen analyses yield a low intercept age of 322 ± 7 Ma and a $^{206}Pb/^{238}U$ weighted average age of 320 ± 5 Ma (Fig. 4d). For Group 4, three zircon grains yield apparent $^{206}Pb/^{238}U$ ages of 283, 296 and 304 Ma, respectively (Fig. 4a). All analyses display very low Th and U contents (Th <4 ppm, U < 36 ppm), and most of the Th/U ratios are less than 0.03. No significant rare earth elements (REEs) differentiation is observed between each analysis (Fig. 4e). All analyses have low total REEs (7.73–41.76 ppm) and HREEs (7.47–40.11 ppm), with Sm_N/Yb_N = 0–0.44, and show depletion in LREEs, enrichment in MREEs and nearly horizontal HREEs profile. Most of the analyses display negative Eu anomaly (δEu = 0.50–0.92), with only few exceptions.

4.2.2. Sample CC28

Zircons from sample CC28 display subhedral to euhedral shapes in size of 100 to 200 μm. Most zircons show core-rim structure in CL images, and are characterized by grey-white homogeneous cores surrounded by structureless dark-grey rims (Fig. 3b). Both zircon domains lack oscillatory zoning, consistent with diagnostics of metamorphic recrystallization. Thirty U-Pb analyses from 22 grains define four age groups through integration of mineral inclusions, CL images and ages (Fig. 5a). The isotope data and trace elements in zircons are listed in Appendix 2 (Table S3). For group 1, eight analyses of the metamorphic cores with rutile and garnet inclusions yield a lower intercept age of 335 ± 11 Ma and a $^{206}Pb/^{238}U$ weighted average age is 334 ± 7 Ma (Fig. 5b). Th, U and Th/U ratios of Group 1 are very low (Th < 2.2 ppm, U < 57 ppm, Th/U < 0.06). For Group 2, one spot yields a $^{206}Pb/^{238}U$ apparent age of 355 ± 14 Ma (Fig. 5a). For Group 3, seventeen analyses for the rims with plagioclase inclusions (one exception that include garnet) yield a lower intercept age of 315 ± 4 Ma and a $^{206}Pb/^{238}U$ weighted average age of 316 ± 2 Ma (Fig. 5c). They have very low Th (<3.5) and higher U contents (13.2–780 ppm) than group 1. Their Th/U ratios are less than 0.1. For Group 4, two analyses yield $^{206}Pb/^{238}U$ apparent ages of 297 and 300 Ma (Fig. 5a). The REEs in the metamorphic zircon cores (Group 1) are characterized by negative Eu anomalies (δEu = 0.44–0.75), low total REEs (6.54–31.18 ppm), HREEs (6.37–30.40 ppm) and Sm_N/Yb_N (0.00–0.13) (Fig. 5d). The metamorphic rims (Group 3) have relatively higher total REEs (9.83–52.90 ppm) and HREEs contents (9.66–50.70 ppm), as well as Sm_N/Yb_N (0.03–0.21) than the metamorphic cores.

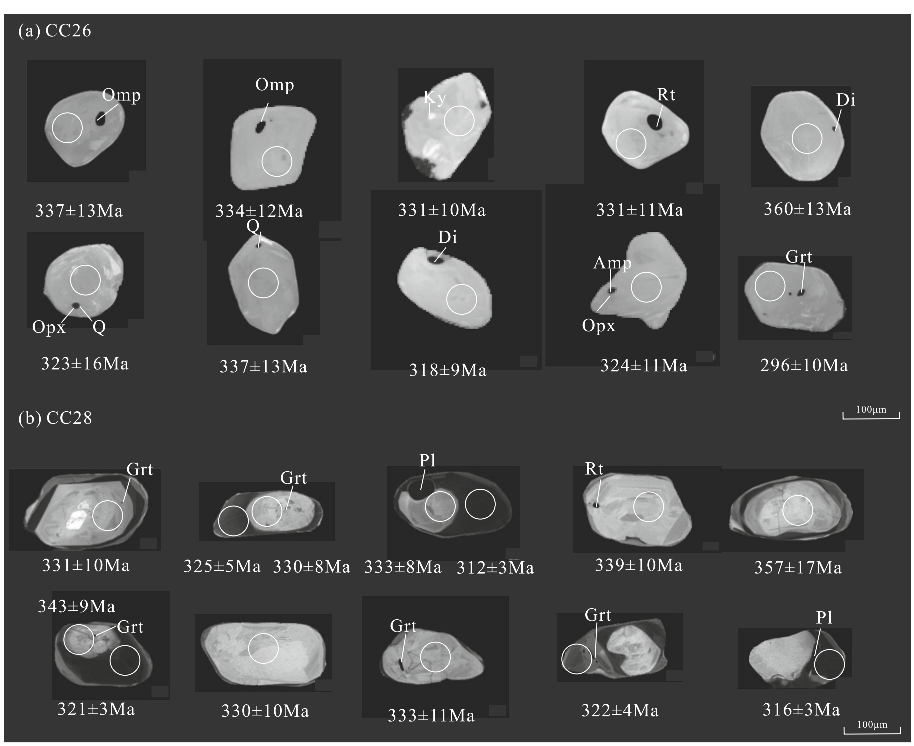

Fig. 3. Representative mineral inclusions in zircons of the samples CC26 (a) and CC28 (b).

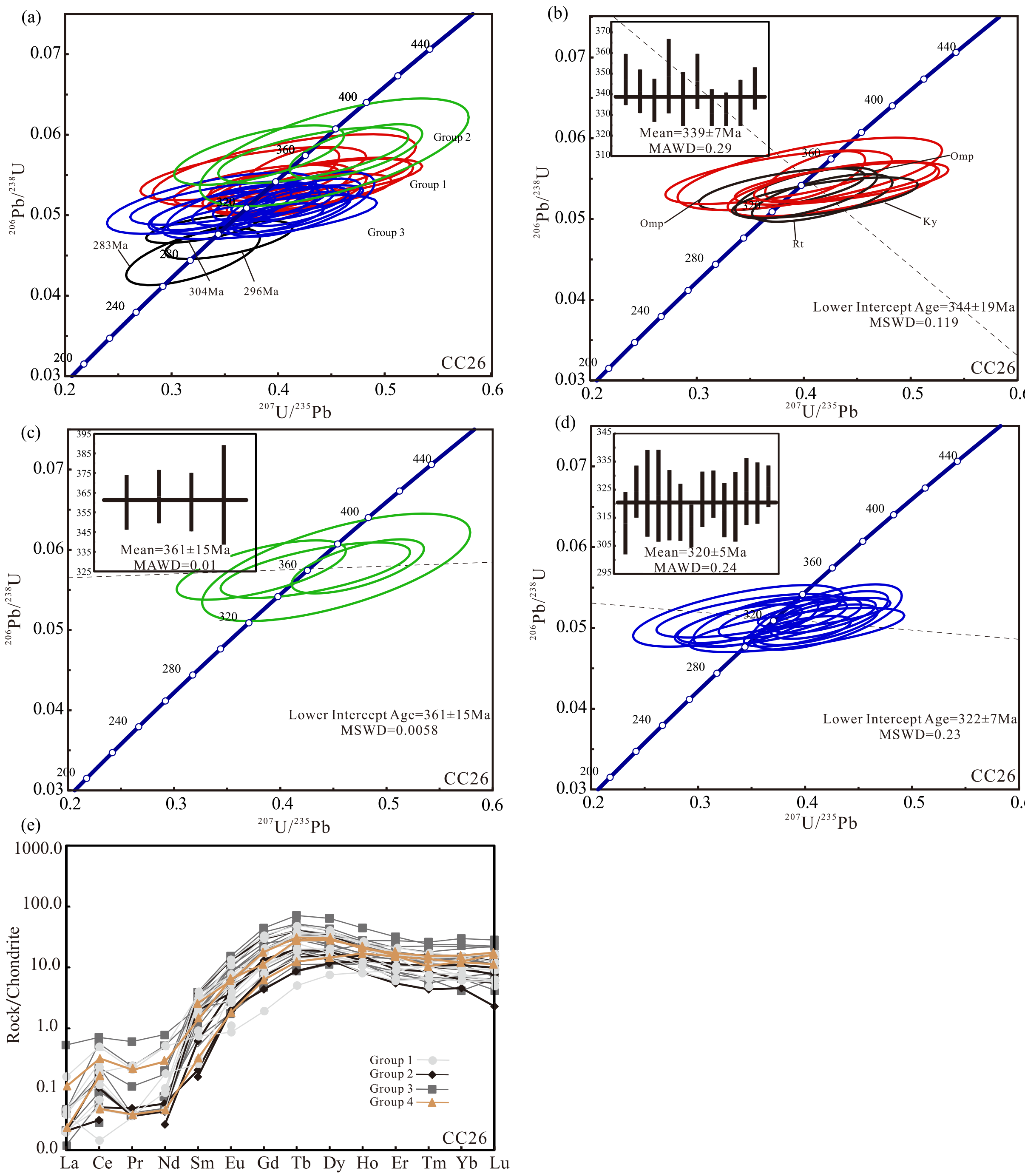

Fig. 4. LA-ICP-MS zircon U-Pb concordia diagrams and weighted average ages diagrams for sample CC26. (a) All analyses, (b) Group 1 analyses with eclogite-facies indicators in some zircon domains, (c) Group 2 analyses with non-eclogite-facies indicators, (d) Group 3 analyses with non-eclogite-facies indicators, (e) Chondrite-normalized REE patterns of zircons, normalization after Sun and McDonough (s1989).

5. Discussion

5.1. Chronological controversy: Paleoproterozoic vs. late Paleozoic

The peak metamorphic age of Chicheng eclogites remains contentious, with two conflicting hypotheses, namely the Paleoproterozoic vs. Late Paleozoic. Some studies suggest that the peak metamorphic age was at the Paleoproterozoic (Wang et al., 2002; Wei et al., 2024; Zhang et al., 2016a). The support evidence includes that (1) there are sporadic ~1950–1800 Ma zircon U-Pb age records in the eclogites, and also many in their country rocks (Wei et al., 2024; Zhang et al., 2016a, 2020; Zou et al., 2021); (2) the location of the Chicheng eclogite is at the northern margin of the NCC, where regional Paleoproterozoic metamorphism imprinted the NCC basements (e.g., Zhai, 2009; Zhou et al., 2017). They argued that Late Paleozoic ages reflect reactivation and exhumation during the CAOB orogeny (Zhang et al., 2016a).

The others suggested that the Chicheng eclogite was formed at the Late Paleozoic because of dominant 315–360 Ma zircon U-Pb ages in eclogites (Chu et al., 2013; Kong et al., 2011; Li et al., 2022; Ni et al., 2004, 2006; Wang, 2010; Yan et al., 2025). They emphasized that a few 440–420 Ma oscillatory-zoned zircon cores in eclogites potentially represent protolith formation ages (Ni et al., 2004, 2006). The

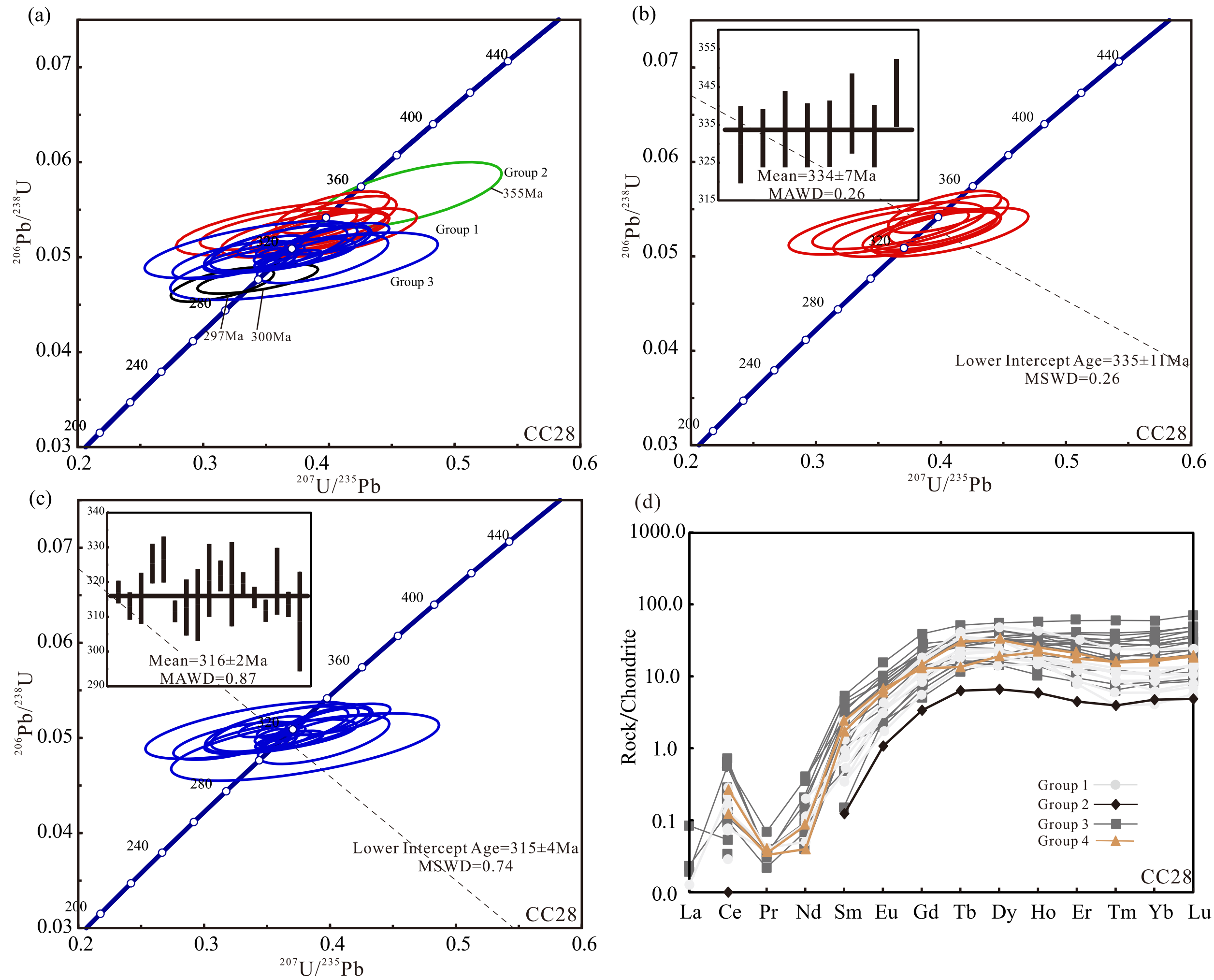

Fig. 5. LA-ICP-MS zircon U-Pb concordia diagrams and weighted average ages diagrams for sample CC28. (a) All analyses, (b) Group 1 analyses of the zircon cores, (c) Group 3 analyses of the zircon rims with non-eclogite-facies indicators, (d) Chondrite-normalized REE patterns of zircons, normalization after Sun and McDonough (1989).

1950–1800 Ma zircon U-Pb ages in eclogites might be inherited or relic (e.g., Yan et al., 2025). Furthermore, these Late Paleozoic metamorphic ages were further divided into three groups of ~355 Ma, ~341 Ma and ~ 320 Ma, correlating with the eclogite-facies, retrograde granulite-facies, and amphibolite-facies ages, respectively (Chu et al., 2013; Kong et al., 2011).

The key points for above controverses are that no reliable links between zircon U-Pb ages and mineral assemblages have been found. To avoid this limitation, Yan et al. (2025) recently performed in-situ LA-ICPMS garnet dating analyses on two retrograde eclogite samples from the Chicheng area. Their analytical results yielded Lu-Hf ages ranging from 354 ± 91 Ma to 369 ± 89 Ma and U-Pb ages of 245 ± 180 Ma to 335 ± 27 Ma. Based on these data, they proposed a Late Paleozoic rather than Paleoproterozoic formation age for the Chicheng eclogites, although the uncertainties of their measurements are large. However, alternative explanations may also exist due to lack of detailed knowledge of Lu and Hf distribution patterns within the studied garnet crystals in Yan et al. (2025). First, the LA-ICPMS garnet Lu-Hf isochron likely represents a mixture age if original Lu and Hf are zoned (cf., Cheng, 2018; Kelly et al., 2011; Lapen et al., 2003). Second, if Lu and Hf exhibit homogeneous distributions within garnet grains, this may indicate post-crystallization homogenization processes, in which case the Lu-Hf age would represent the timing of the latest thermal resetting event rather than original crystallization age. Consequently, the currently available evidence remains insuffcent to definitively establish which age group represent the peak metamorphic ages of the Chicheng eclogites.

5.2. Deciphering Zircon U-Pb ages

This study establishes definitive correlations between zircon domains and mineral assemblages through integration of indicator mineral inclusions with CL images. Four age groups were confidently identified. The zircon domains with omphacite, kyanite or rutile from sample CC26 yield U-Pb age of 339 Ma, and the metamorphic zircon cores of sample CC28 yield U-Pb age of 334 Ma, representing the peak metamorphic ages (Group 1). The U-Pb ages of the zircon domains with non-eclogite-facies indicator minerals were divided into three groups: (1) some are much older than the peak metamorphic ages, yielding U-Pb ages of ~360 Ma (Group 2). The mineral inclusions in zircon consist of amphibole and diopside, which may represent prograde relic minerals. (2) Other ages are younger than the Group 1, with inclusions of plagioclase, orthopyroxene, amphibole, ilmenite, quartz and garnet, which yield U-Pb age of 316 Ma and 320 Ma for sample CC26 and CC28 (Group 3), respectively. Besides, a few zircon domains with persistent mineral garnet (maybe unstable) yield scattered U-Pb ages of 280–304 Ma (Group 4), which are possibly related to post-collisional thermal event in the study area (e.g., Chu et al., 2013).

The three predominant metamorphic ages groups (357–361 Ma, 339–334 Ma and 320–316 Ma) derived from the studied samples are similar with those in Kong et al. (2011) and Chu et al. (2013), but distinct interpretations are proposed here. This study prefers to interpret them as the pre-eclogite-facies, peak eclogite-facies and post-eclogite-facies metamorphism stages, respectively.

5.3. Tectonic implications

Some studies suggest that the Hongqiyingzi Complex, the host of the Chicheng eclogite, in the north side of the Chicheng-Chongli shear zone are counterpart of the Dantazi Complex, which has suffered extensive Paleoproterozoic HP-HT granulite-facies metamorphism. The new findings here indicate that the Hongqiyingzi Complex exhibits distinct Late Paleozoic metamorphic history compared to the Dantazi Complex. The divergence evidence includes: (1) lithological assemblages in the two sides of the Chicheng-Chongli shear zone are different. The serpentinized peridotites and retrograde eclogites are unique to the Hongqiyingzi Complex, which have not been reported in the Dantazi complex. (2) The Hongqiyingzi Complex suffered intensive and extensive Late Paleozoic (315–360 Ma) metamorphic overprint; while the Dantazi Complex are dominated with Neoarchean and Paleoproterozoic ages with rare Late Paleozoic metamorphic zircon U-Pb ages (e.g., Li et al., 2022; Liu et al., 2007). (3) A few oscillatory zoned zircon relic cores in the garnet-bearing plagioclase gneisses from the Hongqiyingzi Complex, having ages of 369–1855 Ma may represent detrital zircon ages and suggest that their sedimentary ages should be possibly younger than 369 Ma (Kong, 2012). Therefore, the Hongqiyingzi Complex (hosting the Chicheng eclogite) was formed during the Late Paleozoic (e.g., Wang et al., 2012; Yan, 2008). The Paleoproterozoic zircons likely represent inherited relicts from protolith sources and/or xenocrystic incorporation during tectonic processes.

In structural context, the north-vergent thrust systems developed cratonward along northern margin of the NCC (e.g., Wang et al., 2013; Zhang et al., 2014) may facilitate the eclogite emplacement. The locally accompanied serpitinized peridotites further suggest that the Chicheng eclogites might be extruded from mantle depth to surface. Some Late Paleozoic granite veins intruded the eclogites, which may be formed during the exhumation of the Chicheng eclogites (Wang, 2010). Besides, considerable Late Paleozoic continental arc related granitoids are developed along the northern margin of the NCC (e.g., Zhang et al., 2007a).

Therefore, this study suggests that the Chicheng eclogite record Late Paleozoic (334–339 Ma) orogenic processes of the CAOB, overprinting earlier Neoarchean-Paleoproterozoic basement. Integrated zircon and mineral inclusions chronometry provides definitive constraints for the peak metamorphic ages. This revised chronology repositions the Hongqiyingzi Complex as a key record of Phanerozoic plate interactions along the NCC northern margin, and future work should prioritize their tectono-metamorphic processes.

6. Conclusions

(1) Eclogite-facies indicators of omphacite (Jd_{21-26}), kyanite and rutile, non-eclogite-facies indicators of diopside, plagioclase, orthopyroxene, amphibole and ilmenite, and persistent minerals of garnet and quartz were recognized for the first time in zircons from the Chicheng eclogite, which establish direct links between zircon domains and metamorphic assemblages.

(2) The Chicheng eclogites are now constrained to a Late Paleozoic formation age, distinct from earlier Paleoproterozoic estimates. Three age groups of 357–361 Ma, 339–334 Ma and 320–316 Ma are interpreted to represent the prograde, peak eclogite-facies, and retrograde metamorphic ages, respectively. The Paleoproterozoic zircons likely represent inherited relicts or xenocrysts. The formation of the Chicheng eclogites was possibly related to the subduction-collision processes of CAOB.

CRediT authorship contribution statement

Xiao-Bo Wang: Visualization, Investigation, Data curation, Writing – original draft. **Jia-Lin Wu:** Supervision, Methodology, Investigation, Conceptualization, Writing – review & editing. **Ming-Guo Zhai:** Validation, Conceptualization, Writing – review & editing. **Le Zhang:** Investigation, Writing – review & editing. **Bo Hu:** Conceptualization, Writing – review & editing.

Declaration of competing interest

We declare that there is no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lithos.2025.108094.

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