

Origin and Geological Significance of the Cambrian–Permian Mafic-Felsic Magmatic Rocks in the Longshenggeng Area of the East Kunlun Orogenic Belt

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ABSTRACT: A set of ultramafic-mafic-felsic rock assemblages was discovered in the Longshenggeng area of the eastern part of the East Kunlun orogenic belt. Petrography, chronology and whole-rock geochemistry were conducted on this set of intrusive rock assemblages. U-Pb dating of apatite shows that the lherzolite formed at 492 ± 5 Ma, the granite at 473 ± 6 Ma, and the diabase at 260 ± 14 Ma, respectively. The lherzolites belong to a supra-subduction zone type (SSZ-type) ophiolite component above a subduction zone; the granites formed in an ocean-continent subduction setting; and the diabases represent products of partial melting of an asthenospheric mantle at shallow depth. The East Kunlun orogenic belt features the East Kunzhong and Buqingshan-Animaqing ophiolitic mélange belts, with the latter representing remnants of the Proto-Tethys Ocean. The Late Cambrian lherzolites and granites in the Longshenggeng area were magmatic products of the back-arc ocean basin and island arc formed during the northward subduction of the Proto-Tethys Ocean. Subsequently, extensive island arc magmatism occurred from the Late Permian to Middle Triassic, driven by the northward subduction of the Paleo-Tethys Ocean beneath the East Kunlun Block. The diabase may have formed during the transition from subduction to post-collisional extension.

KEY WORDS: apatite U-Pb dating, lherzolite, granite, diabase, East Kunlun orogenic belt.

0 INTRODUCTION

The East Kunlun orogenic belt is located in the north-eastern part of the Qinghai-Tibet Plateau and is an important component of the Central orogenic belt (Su et al., 2023; Zhang et al., 2021; Yang et al., 2010; Xu et al., 2006) (Figure 1a). This orogenic belt has undergone two significant stages of ocean-continent transition, the Neoproterozoic–Early Paleozoic and the Late Paleozoic–Early Mesozoic (Wang et al., 2004, 1997; Zhang, 2003; Wang et al., 1999; Yin and Zhang, 1997; Pan et al., 1996). The Kunzhong paleo-ocean, which initially opened between 520 and 580 Ma, experienced subduc-

tion and consumption between 454 and 511 Ma, ultimately closing around 444 Ma. This geological process is recorded by the Naj Tal Complex in the western region and the Qingshuiquan ophiolite in the eastern area (Figure 1b). Previous studies have mostly focused on the early evolution of the Proto-Tethys Ocean in the East Kunlun region, while research on the final closure, collision, and post-collision processes of the Kunzhong Ocean remains relatively scarce.

Over the past few years, during the extensive geological investigation and mineral exploration in the Longshenggeng area, east of Qingshuiquan ophiolite in the eastern part of the East Kunlun orogenic belt, a suite of mafic-ultramafic complexes was discovered by the Third Geological Exploration Institute of the Qinghai Provincial Non-Ferrous Metals Bureau. This discovery provides a new window for further study of the mafic-ultramafic rocks in the East Kunlun region, and sheds new light on the broader tectonic evolution of this orogenic belt. In this

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Manuscript received March 22, 2024.

Manuscript accepted September 3, 2024.

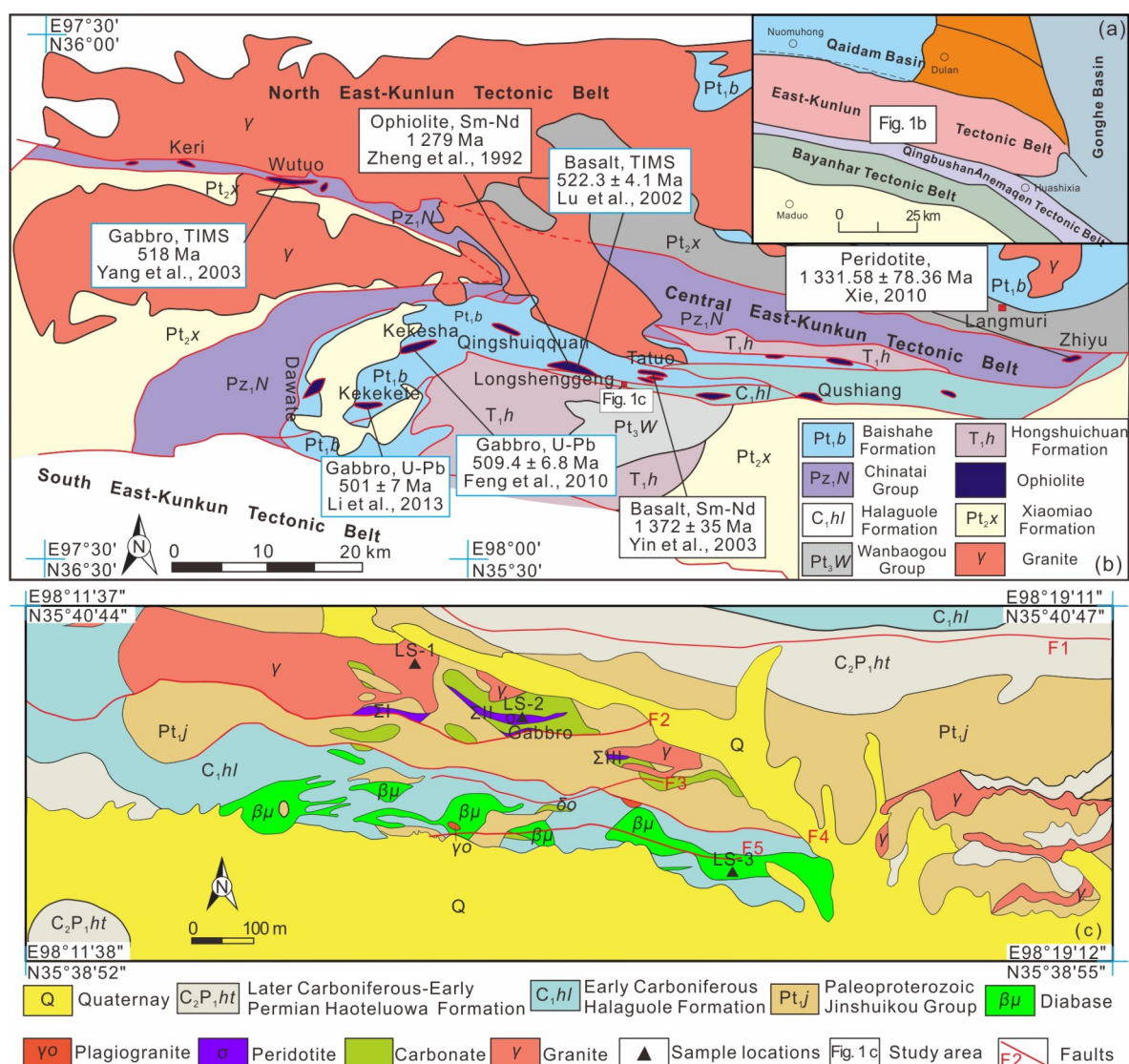


Figure 1. (a) Schematic geotectonic framework in the eastern part of East Kunlun tectonic belt; (b) distribution map of ophiolites in the Wutuo-Qingshuiquan-Tatuo-Qushiang area in the East Kunlun ophiolite belt (modified from Wei, 2015); (c) geological map of the Longshenggeng region.

study, systematical sampling of the discovered mafic-ultramafic complexes and adjacent granite bodies was conducted. An integrated study was undertaken on the collected samples, encompassing whole-rock major and trace element analysis and apatite U-Pb geochronology. The findings from this study help determine the genesis and origin of the samples, providing crucial insights into the tectonic-magmatic evolution of the Late Cambrian–Permian Period in the East Kunlun area.

1 GEOLOGICAL BACKGROUND

The study area is located within the East Kunlun orogenic belt (Figure 1a). The dominant exposed strata in this region consist of the Paleoproterozoic Jinshui Kou Group (Pt₂j), the Early Carboniferous Halaguole Formation (C₁hl), and the Late Carboniferous–Early Permian Haoteluowa Formation (C₂P₁ht) (Wang, 2019), along with Quaternary sediments (Q) (Figure 1c). The region contains a widespread distribution of magmatic rocks, primar-

ily controlled by east-west trending tectonic zones. The rocks are predominantly intermediate-felsic, with minor basic-ultrabasic rocks. Granite plutons are primarily distributed in the northern and eastern parts of the study area, intruding into the Jinshui Kou Group and occurring as stocks (Figure 1c). Those in the eastern part are closely associated with faults and exhibit intense mingling with the surrounding rocks. The central part of the study area contains a high concentration of mafic-ultramafic rocks, predominantly lherzolites and dolerites.

Lherzolite is distributed in the central part of the study region, and is primarily related to the F2 fault, where it is in fault contact with the Jinshui Kou Group gneiss. This study focuses on three lherzolite bodies (ΣI–III, Figure 1c). The ΣI lherzolite body exhibits an east-west trending, band-like distribution, measuring approximately 1.2 km in length, 60–200 m in width, and covering an area of 0.18 km². The ΣII lherzolite body also has a nearly east-west trending, band-like distribution, with a

length of about 1.6 km, a width ranging from 50 to 180 m, and an area of 0.13 km². The ΣIII Iherzolite body, the smallest in terms of exposed area, measures approximately 0.6 km in length and 60 m in width, covering an area of 0.04 km². It also exhibits an east-west trending, band-like distribution. Hand specimens of Iherzolite are gray-black, displaying a mesh and massive structure (Figures 2a and 2b). They are primarily composed of olivine (55%), clinopyroxene (15%), orthopyroxene (15%), along with a small amount of spinel and sulfides (Figure 2c). Olivine is anhedral and granular, with grain sizes mostly between 1.0 and 1.5 mm, exhibiting well-developed cleavage. Serpentinization occurs intensively along the edges and cleavages of the olivine, resulting in the precipitation of fine-grained magnetite. Clinopyroxene mainly occurs as subhedral, columnar, or granular forms, commonly filling the interstices between olivine grains. Sulfides are irregularly distributed in the interstices of olivine, forming sideronitic structures and disseminated textures.

Granite primarily outcrops in the northwestern and eastern regions of the study area, covering an area of approximately 2.11 km² and displaying linear and bead-like distributions (Figure 1c). The rocks are gray-white in color and exhibit fine-grained and massive textures (Figure 2d). The main mineral constituents are quartz (65%), plagioclase (15%), potassium feldspar (10%), and biotite (5%) (Figures 2e and 2f). Some biotite has undergone sericitization and chloritization. Accessory minerals include apatite, zircon, and opaque minerals.

Diabase is present in the central portion of the study area, primarily occurring as stocks and dikes, spanning about 1.22 km². These rocks are dark gray-green in color and exhibit typical diabasic and massive textures (Figures 2g and 2h). They are primarily composed of clinopyroxene (35%–40%) and plagioclase (55%–60%), with minor opaque minerals (Fe-Ti oxides) (Figure 2i). Clinopyroxene occurs as irregular grains filling the gaps between plagioclases, and most orthopyroxene has undergone alteration to amphibole. Plagioclase typically appears in relatively euhedral tabular shapes, with sericite alteration.

2 ANALYTICAL METHODS

To accurately determine the formation age of mafic-felsic magmatic rocks in the Longshenggeng area and to elucidate their petrogenesis, this study utilized LA-ICP-MS U-Pb isotopic dating on apatite, complemented by comprehensive major and trace element analyses of whole-rock samples. The dated samples include grayish-black Iherzolite (LS-2, E98° 15'14", N35° 40'08"), granite (LS-1, E98° 14'34", N35° 40'26") and diabase (LS-3, E98° 16'38", N35° 39'18") (Figure 1c).

2.1 Apatite U-Pb Geochronology

Apatite separation was completed at the Rock and Mineral Analysis and Testing Center of the Hebei Langfang Xinhang Surveying and Mapping Institute. First, the samples were crushed, followed by flotation and density separation. After rinsing, the apatite grains were finally

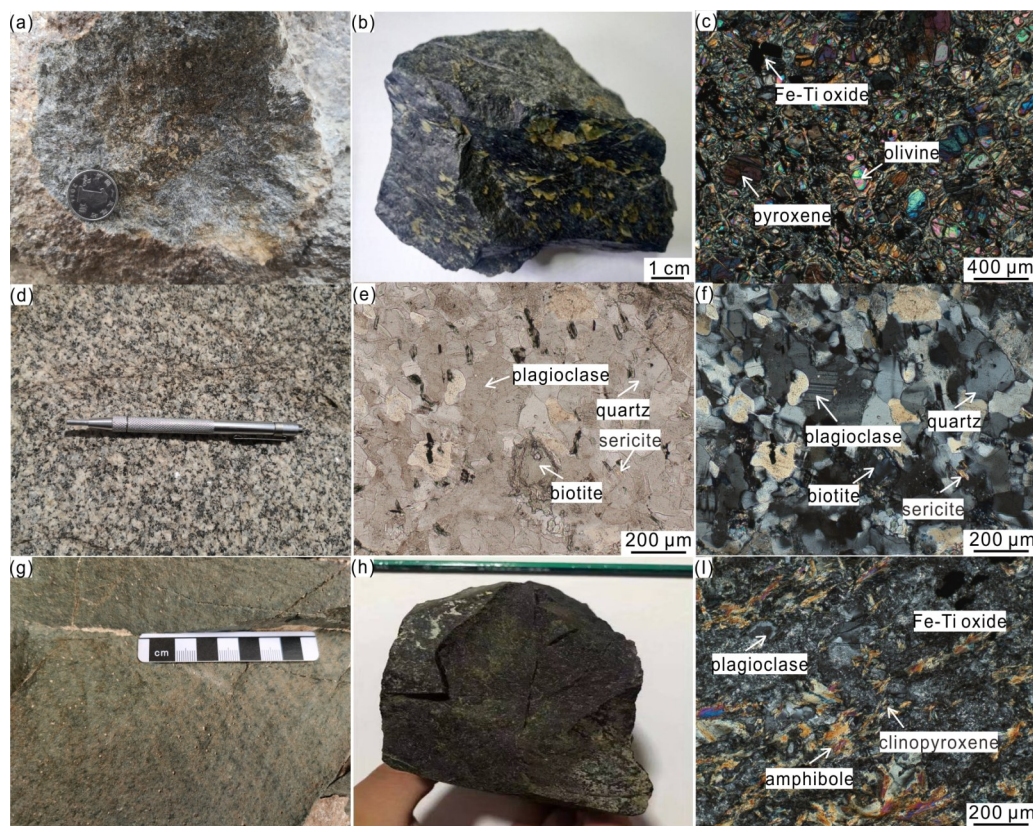


Figure 2. Field outcrops and photomicrographs of mafic-felsic magmatic rocks in the Longshenggeng area, East Kunlun region. Iherzolite (a)–(c); granite (d)–(f); diabase (g)–(i).

selected under a binocular microscope (Su and Zhang, 2012). The prepared apatite grains were mounted on a target with epoxy resin, then ground and polished until a fresh cross-section of each grain was exposed. After transmitted and reflected light imaging under a microscope, cathodoluminescence (CL) imaging was performed. CL images were obtained using the CITL CL8200 MK5-2 cathodoluminescence scanner at the Global Tectonics and Lithosphere Institute of the College of Earth Sciences, China University of Geosciences (Wuhan).

LA-ICP-MS apatite U-Pb dating was completed at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (Wuhan). The laser ablation system was manufactured by Resonetics (Resonetics-S155). An ArF excimer laser with a 193 nm UV beam was focused on the apatite surface. The laser spot diameter was 44 μm , with the ablation frequency of 8 Hz, and the ablation lasted for 40 s. High-purity He gas was used as the carrier gas, mixed with Ar gas and a small amount of N_2 gas, and transported to the mass spectrometer. The inductively coupled plasma mass spectrometer was manufactured by Thermo Fisher Scientific (iCAP Qc). During the analysis, Madagascar apatite (MAD, average $^{206}\text{Pb}/^{238}\text{U}$ age of 474.25 ± 0.41 Ma) was used as the external standard for elemental fractionation correction, while NIST SRM 612 was served for signal drift correction. Calcium (Ca) was used as an internal standard for the determination of the major and trace element abundances. The method for correcting common Pb in this study follows the procedure described by Chen and Simonetti (2013).

2.2 Whole-Rock Major and Trace Element Analysis

Whole-rock major and trace element analyses were performed at the Xi'an Institute of Geological Mineral Resources Research and the Xi'an Center for Mineral Resources Investigation, respectively. Fresh, unaltered samples were selected to ensure the precision of the results. Major element analysis was performed using XRF (PW4400, PANalytical), with an error in the analysis of less than 1 %. Trace element concentrations were obtained using ICP-MS (XSERIES 2, Thermo Scientific), with an analytical error generally not exceeding 5%. However, for volatile elements and trace elements with extremely low abundances, analytical errors can reach up to 10%.

3 RESULTS

3.1 Apatite U-Pb Ages

The apatite in Iherzolite, granite, and diabase samples from the study area mostly exhibits subhedral to euhedral morphologies, with lengths ranging from 50 to 300 μm and length-to-width ratios varying from 2 : 1 to 4 : 1. Under transmitted light, the apatite surfaces appear clean and nearly transparent, with no visible impurities or inclusions. Under cathodoluminescence imaging, the apatite luminesces uniformly with rare cracks and inclu-

sions (Figure 3), indicating typical characteristics of magmatic apatite (Dempster et al., 2003).

In the granite sample (LS-1), 26 analysis points of apatite were conducted. Th content of apatite ranges from 1.34×10^{-6} to 98×10^{-6} (average 18.3×10^{-6}), and U content ranges from 33.0×10^{-6} to 1297×10^{-6} (average 764×10^{-6}), with Th/U ratios ranging from 0.01 to 0.09. A lower intercept age of 469 ± 9 Ma (2σ ; $n = 26$, MSWD = 4.4) was obtained from the Tera-Wasserburg diagram (Figure 4c). After corrections using the ^{207}Pb method, the $^{206}\text{Pb}/^{238}\text{U}$ ages for the apatite grains range from 441 and 498 Ma, yielding a weighted average age of 473 ± 6 Ma (2σ ; $n = 26$, MSWD = 4.4) (Figure 4d). This age aligns with the lower intercept age within error, indicating that the granite's emplacement age is around 470 Ma.

Apatite grains in the diabase sample (LS-3) have Th and U contents ranging from 5.19×10^{-6} to 77.8×10^{-6} (average 30.0×10^{-6}) and from 14.7×10^{-6} to 115×10^{-6} (average 39.8×10^{-6}), with Th/U ratios ranging from 0.28 to 1.48. Fifteen analyses give a lower intercept age of 270 ± 21 Ma (2σ ; $n = 15$, MSWD = 1.8) on the Tera-Wasserburg diagram (Figure 4e). After correction using the ^{207}Pb method, apatite grains range in age from 230 to 333 Ma, yielding a weighted average age of 260 ± 14 Ma (2σ ; $n = 15$, MSWD = 16) (Figure 4f). This age closely aligns with the lower intercept age from the Tera-Wasserburg plot within error, indicating that the emplacement of the diabase occurred around 260 Ma. Notably, the MSWD value for the apatite sample is relatively high. In Figure 4c, most data points are concentrated in the lower part of the curve, with only one point in the upper part. This imbalance may affect the accuracy of the fit and contribute to the high MSWD value.

3.2 Major Element Geochemistry

The major element results for the Iherzolite, granite and diabase are presented in Table S2. The loss on ignition (LOI) of the Iherzolite samples from the Longshengeng area is high, ranging from 12.54 wt.% to 12.99 wt.%, likely due to the intense serpentinization of the samples. Normalized results show that the contents of SiO_2 , TiO_2 , Al_2O_3 , CaO, MgO, and Fe_2O_3 vary from 38.74 wt.% to 39.44 wt.%, 0 to 0.03 wt.%, 0.44 wt.% to 1.07 wt.%, 0.08 wt.% to 0.12 wt.%, 36.56 wt.% to 36.93 wt.%, and 8.07 wt.% to 8.57 wt.%, respectively. The calculated $\text{Mg}^\#$ is high, ranging from 89.5 to 90.0. In the SiO_2 - K_2O diagram, the samples fall near the boundary between the calc-alkaline series and the low-K (tholeiitic) series (Figure 5a). The Iherzolite samples in the TAS diagram are plotted within the gabbro field (Figure 5b).

The granite has high and limited SiO_2 content, from 73.12 wt.% to 73.86 wt.%. It shows high contents of K_2O (3.92 wt.% to 4.28 wt.%), Na_2O (2.51 wt.% to 2.60 wt.%) and total alkali $\text{Na}_2\text{O} + \text{K}_2\text{O}$ (6.43 wt.% to 6.88 wt.%), along with low MgO (0.95 wt.% to 1.17 wt.%) and CaO (0.44 wt.% to 0.50 wt.%). The samples in the SiO_2 - K_2O diagram are located within the high-K (calc-alkaline) series area (Figure 5a). The samples all fall within the granite

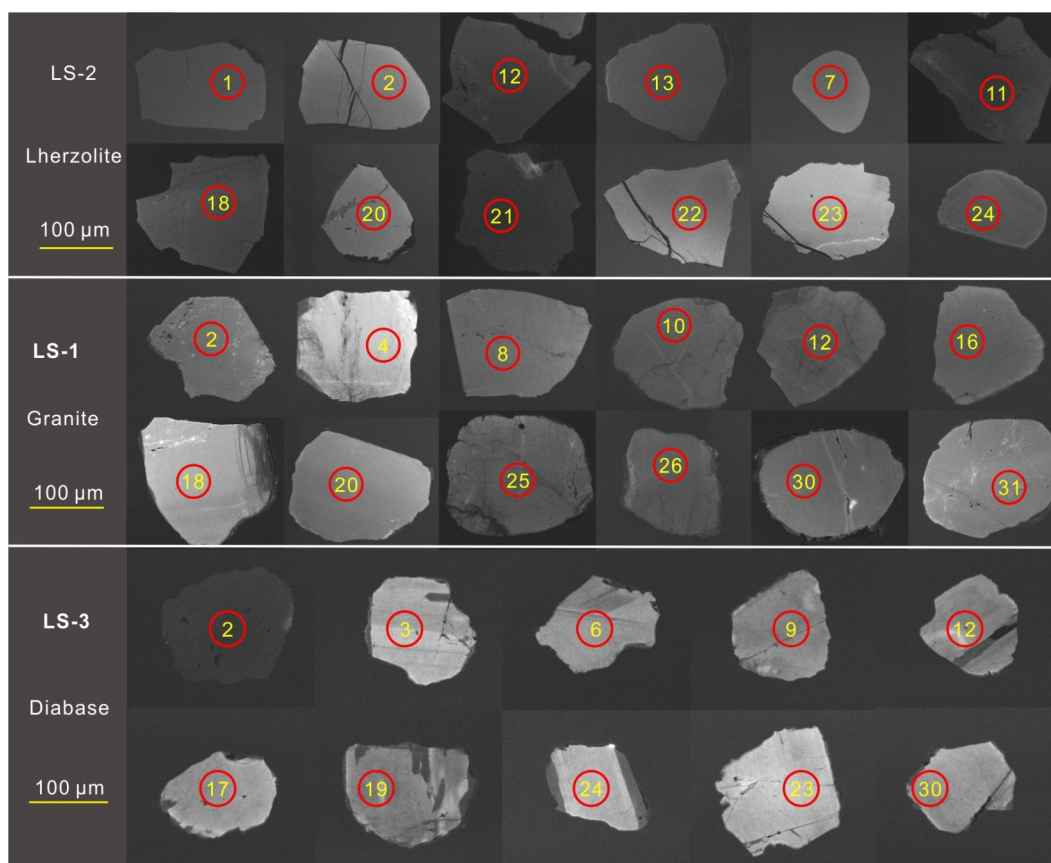


Figure 3. Cathodoluminescence images of apatite from the studied Iherzolite, granite, and diabase. LA-ICP-MS U-Pb isotope dating results of apatite in Iherzolite, granite, and diabase are presented in Table S1. In the Iherzolite sample (LS-2), apatite grains show Th and U contents ranging from 33.1×10^{-6} to 295×10^{-6} (average 114×10^{-6}) and from 79.1×10^{-6} to 590×10^{-6} (average 291×10^{-6}), with Th/U ratios between 0.22 and 0.68. Sixteen valid analyses yield a lower intercept age of 496 ± 6 Ma (2σ ; $n = 16$, MSWD = 1.3) on the Tera-Wasserburg diagram (Figure 4a). After correction using the common ^{207}Pb method, apatite grains exhibit $^{206}\text{Pb}/^{238}\text{U}$ ages between 479 and 511 Ma, yielding a weighted average age of 492 ± 5 Ma (2σ ; $n = 16$, MSWD = 1.4; Figure 4b). This age is consistent with the lower intercept age obtained from the Tera-Wasserburg diagram within error, indicating it represents the crystallization age of the Iherzolite.

field on the TAS diagram (Figure 5b), consistent with petrographic identification.

The diabase samples have relatively low SiO_2 (49.72 wt.% to 49.82 wt.%), K_2O (uniformly at 0.36 wt.%), but high concentrations of TiO_2 (1.58 wt.% to 1.61 wt.%) and $\text{Fe}_2\text{O}_3^{\text{T}}$ (15.19 wt.% to 15.57 wt.%). The Al_2O_3 and MgO contents are moderate, ranging from 12.45 wt.% to 12.83 wt.% and 6.25 wt.% to 6.52 wt.%, respectively, with $\text{Mg}^\#$ from 44.9 to 45.3, classifying within the sub-calc-alkaline series. In the SiO_2 - K_2O diagram, the samples belong to the low-K (tholeiitic) basalt series (Figure 5a). The samples are positioned within the subalkaline gabbro field in the TAS diagram (Figure 5b).

3.3 Trace Element Geochemistry

The Iherzolite samples exhibit low total REE (ΣREE) concentrations, ranging from 1.52×10^{-6} to 6.24×10^{-6} . These values are similar to the REE content observed in typical ophiolite-type Iherzolite worldwide. The REE distribution patterns highlight LREE enrichment and HREE depletion, showing a right-tilted pattern with $(\text{La}/\text{Yb})_{\text{N}} = 6.66$ – 8.15 , $(\text{La}/\text{Sm})_{\text{N}} = 2.73$ – 3.36 , and $(\text{Gd}/\text{Yb})_{\text{N}} = 1.65$ –

1.80 (Figure 6a). The primitive mantle-normalized trace element diagram reveals enrichment of large ion lithophile elements (such as Rb, Th, U) and depletion of high field strength elements (such as Nb, Zr, Hf) (Figure 6b).

The total REE content in the granite samples are relatively high, ranging from 187×10^{-6} to 249×10^{-6} , with an average of 211×10^{-6} . The REE distribution pattern is steeply right-tilted, showing significant differentiation between LREEs and HREEs, with $(\text{La}/\text{Yb})_{\text{N}} = 7.48$ – 8.87 , $(\text{La}/\text{Sm})_{\text{N}} = 2.79$ – 3.07 , and $(\text{Gd}/\text{Yb})_{\text{N}} = 1.98$ – 2.14 (Figure 6c). A notable negative Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.32$ – 0.38) is observed. In the primitive mantle-normalized trace element spider diagram, the granite samples exhibit relative enrichments in elements such as Rb, Th, La, Pb, Nd, and Sm, and relative depletions in Ba, Nb, Ta, Sr, Zr, and Eu (Figure 6d).

The diabase samples display low total REE concentrations, ranging from 52.8×10^{-6} to 61.0×10^{-6} , with an average of 56.6×10^{-6} . The REE distribution pattern generally shows slight LREE enrichment and a flat HREE pattern, with $(\text{La}/\text{Yb})_{\text{N}} = 1.26$ – 1.39 , $(\text{La}/\text{Sm})_{\text{N}} = 1.07$ – 1.16 , and $(\text{Gd}/\text{Yb})_{\text{N}} = 1.09$ – 1.13 , reflecting minimal differentia-

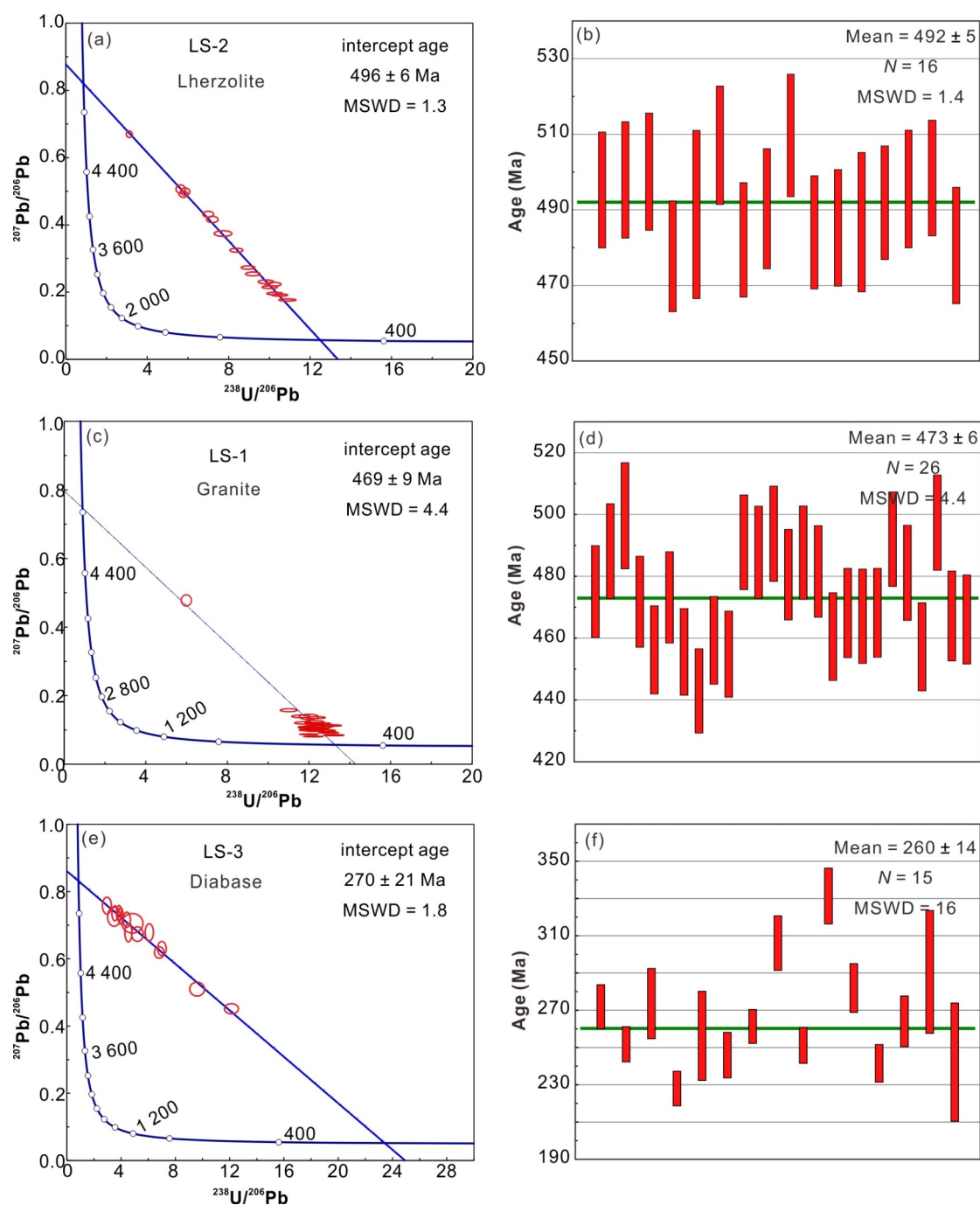


Figure 4. Tera-Wasserburg diagrams (a), (c), (e) and weighted average ages (b), (d), (f) illustrating U-Pb data for apatite from the studied lherzolite, granite and diabase.

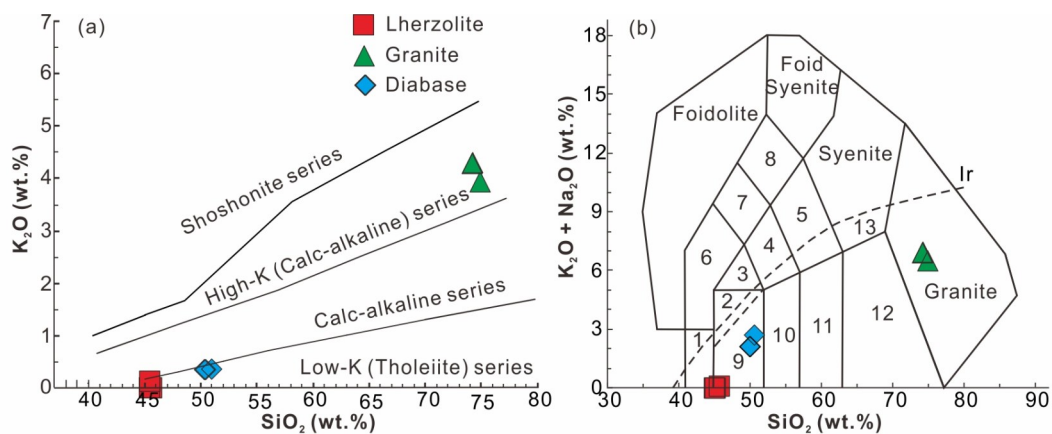
tion between LREEs and HREEs (Figure 6e). A moderate negative Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.74\text{--}0.77$) is present in the REE distribution diagram, likely attributed to the crystal fractionation of plagioclase. Moreover, the diabase samples show relative enrichments in elements such as Rb, Th, Ta, Pb, and Nd and relative depletions in elements such as Ba, Nb, Ce, and Eu (Figure 6f). Collectively, these geochemical characteristics resemble those of island arc magmatic rocks (Yao et al., 2014; Kelemen et al., 1990).

4 DISCUSSION

4.1 Petrogenesis and Formation Environment

4.1.1 Lherzolite

The MgO content and $\text{Mg}^\#$ of the analyzed lherzolite samples are similar to those found in harzburgites in typical ophiolites but significantly higher than those of typical lherzolite (Coleman, 1977). Furthermore, the concentrations of SiO_2 , TiO_2 , Al_2O_3 , and CaO in these samples are significantly lower than the average levels of the primitive mantle. These results suggest that this set of lherzolite rocks may represent residual products of partial melting



1. Peridot-gabbro; 2. alkaline Gabbro; 3. Monzogabbro; 4. Monzodiorite; 5. Monzobite; 6. Foid Gabbro; 7. Foid Monzodiorite; 8. Foid Monzosyenite; 9. sub-alkaline Gabbro; 10. Gabbroic diorite; 11. Diorite; 12. Granodiorite; 13. Quartz Monzonite

Figure 5. Plots of (a) SiO₂ versus K₂O; (b) TAS diagrams of the magmatic rocks in the Longshenggeng area, East-Kunlun tectonic belt ((a), base map according to Peccerillo and Taylor, 1976) and TAS diagram ((b), base map according to Irvine and Baragar, 1971).

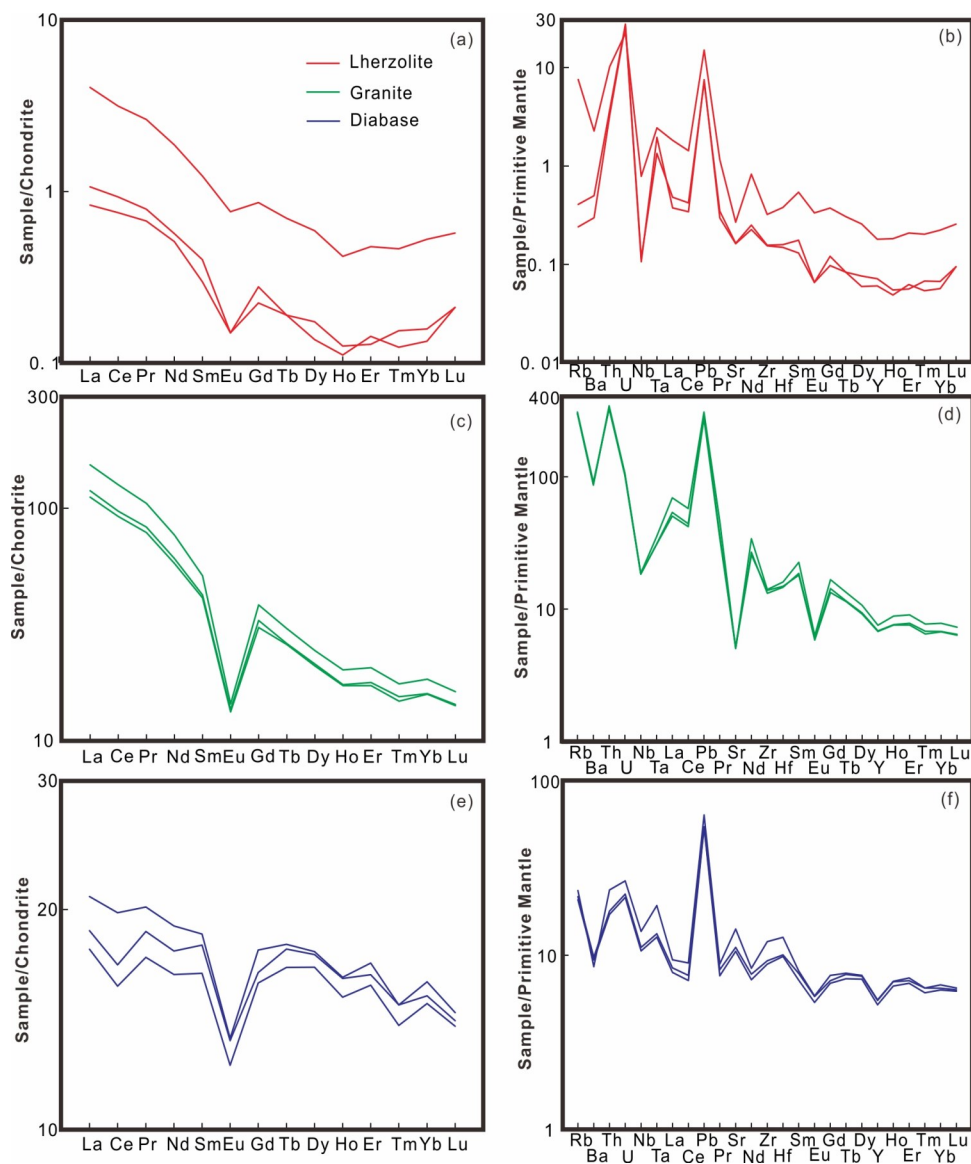


Figure 6. Chondrite-normalized rare earth element patterns (left) and primitive mantle-normalized trace element spidergrams (right) for the magmatic rocks from the Longshenggeng area in the East-Kunlun tectonic belt. Chondrite and primitive mantle values for normalization are from Sun and McDonough (1989).

within the primitive mantle. During the partial melting of mantle peridotites, fusible components, including CaO , Al_2O_3 , SiO_2 , and TiO_2 , predominantly enter the melt phase. In contrast, refractory components, notably MgO , tend to be retained within the residual mantle rocks (Niu et al., 2015). The trace element data further support this interpretation. Relative to the primitive mantle, these lherzolite samples show an enrichment of compatible elements (such as Cr, Co, Ni) and a depletion of incompatible elements (such as Rb, Nb, Ta, Zr, Hf, Ti). Subduction zone metasomatism primarily affects fluid-mobile elements, such as LILE (K, Rb, Sr, Ba) and LREEs (La, Ce), rather than HREEs. Therefore, the impact of subduction zone metasomatism on HREEs is negligible, enabling quantitative modeling of the degree of partial melting of mantle peridotites (Melcher et al., 2002). Based on the fractional melting model of the N-MORB mantle source (Figures 7a and 7b), this study estimates that the lherzolites in the Longshenggong area experienced partial melting ranging from around 15% to 25%. Additionally, elements such as Ti, V, and Yb can be used to accurately simulate compositional variations within the MORB mantle source under different degrees of partial melting and varying oxygen fugacity conditions (Pearce et al., 2000). Figure 7c shows that 13% to 23% partial melting of spinel lherzolite occurred in the Longshenggong lherzolite. Furthermore, Figure 7d demonstrates the variations in partial melting of spinel lherzolite under different oxygen fugacity conditions. The analytical results suggest that the studied lherzolite is the product of 15% to 22% partial melting of spinel lherzolite under high oxygen fugacity conditions. Overall, the Longshenggong lherzolite likely underwent partial melting, influenced by high oxygen fugacity, with a melting extent of 13% to 23%.

Field observations indicate that the lherzolites in the Longshenggong area occur as tectonic slices within the surrounding Paleoproterozoic Jinshuikou Group, displaying a typical “block-matrix” structure characteristic of ophiolitic mélange. Based on the geochemical analysis of the lherzolite samples, it is inferred that these lherzolite blocks represent the mantle lherzolite components within the ophiolite. Pearce et al. (1984) categorized ophiolites based on their tectonic setting into MOR-type (mid-ocean-ridge-type) ophiolites, which formed at mid-ocean ridges, and SSZ-type ophiolites, which formed above subduction zones. Mantle lherzolites in MOR-type ophiolites are primarily characterized by a depletion in LREEs; whereas those in SSZ-type ophiolites are mainly harzburgite, exhibiting an enrichment in LREEs. As previously mentioned, the lherzolites from the Longshenggong area possess high MgO but low SiO_2 , TiO_2 , Al_2O_3 , and CaO contents, and exhibit enrichment in LREEs and LILEs, resembling the features of harzburgites. Therefore, the lherzolites in the Longshenggong area are likely part of SSZ-type ophiolites that formed above a subduction zone.

4.1.2 Granite

The granite in the study area exhibits high SiO_2 and

Al_2O_3 contents, consistent with the characteristics of highly differentiated granites (Wu et al., 2017). In the $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y} - (\text{K}_2\text{O} + \text{Na}_2\text{O})/\text{CaO}$ diagram, all samples fall within the region of highly differentiated granite (Figure 8a). Additionally, these granite samples have relatively low P_2O_5 content of 0.11 wt.% to 0.12 wt.%, indicating that their parent magma underwent fractional crystallization of apatite in the early evolutionary stage. Furthermore, these granites lack signature minerals of peraluminous S-type granites, such as cordierite, muscovite, and garnet. Therefore, these granites are not classified as S-type granites. The ratios of $10\,000 \times \text{Ga}/\text{Al}$ for these samples are between 2.28 and 2.32, with Zr content ranging from 147×10^{-6} to 157×10^{-6} , and $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ content ranging from 270×10^{-6} to 307×10^{-6} . These values are all below the typical discriminant criteria for A-type granites (Whalen et al., 1987). All samples in the Zr-TiO₂ classification diagram fall within the area of I-type granite (Figure 8b).

To summarize, the granites in the Longshenggong region are classified as highly differentiated I-type granite. The REE right-tilted pattern, along with enrichment in LILEs and depletion in HFSEs, is characteristic of Andean-type continental arc granites. This indicates that the granites in the Longshenggong area likely formed within an active continental margin setting related to oceanic-continental subduction.

4.1.3 Diabase

The diabase in the Longshenggong region has a relatively low $\text{Mg}^\#$, with Cr, Co, and Ni contents ranging from 88.9×10^{-6} to 123×10^{-6} , 39.7×10^{-6} to 43.8×10^{-6} , and 59.5×10^{-6} to 62.4×10^{-6} , respectively, all of which are lower than those of primitive basaltic magmas. This suggests that the parent magmas underwent some degree of fractional crystallization. Additionally, the total REE contents of the samples are relatively low, with right-tilted REE distribution patterns showing LREEs enrichment and HREEs depletion, similar to E-MORB. The analyzed samples do not exhibit significant LILE enrichments or negative Nb-Ta-Ti anomalies in the primitive mantle-normalized diagram (Figure 6f), suggesting that the diabase in the Longshenggong region did not originate from enriched continental lithospheric mantle metasomatized by subducted materials. The high TiO_2 content and low La/Ba (0.08–0.11) and La/Nb (0.66–0.73) ratios imply that their magma source may be the asthenosphere mantle. Based on the relatively flat HREE patterns and low La/Yb (1.76–1.94) and Dy/Yb (1.69–1.75) ratios, it is inferred that partial melting of their mantle source occurred at relatively shallow depths within the spinel stability field (Peng et al., 2017). All diabase samples fall within the range of within-plate basalts in the Nb-Zr-Y and Zr/Y-Zr diagrams (Figures 9a and 9b), consistent with their high Zr/Y (4.16–5.32) and Zr/Sm (29.8–37.1) ratios. In summary, the formation of the diabase rocks from the Longshenggong area resulted from partial melting of the asthenosphere mantle at shallow depths under a within-plate setting.

4.2 Significance of Regional Tectonic Evolution

The East Kunlun orogenic belt hosts two essential ophiolitic mélange belts, namely the East Kunzhong ophiolitic mélange belt and the Buqingshan-Animaqing ophiolitic mélange belt (Yang, 2014). The Buqingshan-Animaqing ophiolitic mélange belt, located in the south, formed during the interval of 555–467 Ma and exhibits geochemical characteristics of MOR-type ophiolites. It is considered a representative of the remnants of the main oceanic basin of the Proto-Tethys Ocean (Liu et al., 2011). The East Kunzhong ophiolitic mélange belt in the north is an important boundary dividing the northern and southern sections of the East Kunlun orogenic belt. In its eastern section, ophiolitic mélange rocks such as Qushiang, Tatu, Qingshuiquan, Wutuo, Kekesha-Kekekete, and Acite, are exposed (Wei, 2015). These ophiolitic rocks are classified as SSZ-type ophiolites based on their geochemical properties, indicating they likely formed in a back-arc basin tectonic setting. Previous studies using LA-ICP-MS U-Pb dating of zircon in gabbros from the ophiolites have constrained their formation ages to be-

tween 522 and 481 Ma (Wei, 2015; Feng et al., 2010). The Iherzolites in this study are situated around 10 km east of the Qingshuiquan ophiolite. This study demonstrates that the Iherzolite is a part of the SSZ-type ophiolites formed above a subduction zone. Additionally, LA-ICP-MS U-Pb dating of apatite in the samples suggests a formation age of about 492 ± 5 Ma, consistent with the age of the East Kunzhong ophiolitic mélange belt (Figure 10a). In summary, the Longshenggeng Iherzolite is likely an essential constituent of the East Kunzhong ophiolitic mélange belt.

Notably, significant volcanic arc magmatism is spatially associated with the East Kunzhong ophiolite belt. For instance, the island arc gabbro adjacent to Qingshuiquan ophiolite has a formation age of ~ 452 Ma, the island arc intermediate-mafic complex adjacent to Qushiang ophiolite dates to ~ 456 Ma (Wei, 2015), and the quartz diorite adjacent to the Kekesha-Kekekete ophiolite intruded around ~ 515 Ma (Zhang Y F et al., 2010). Additionally, the granite adjacent to the Longshenggeng ophiolite in this study intruded at ~ 470 Ma. The rhyolite from the Naij

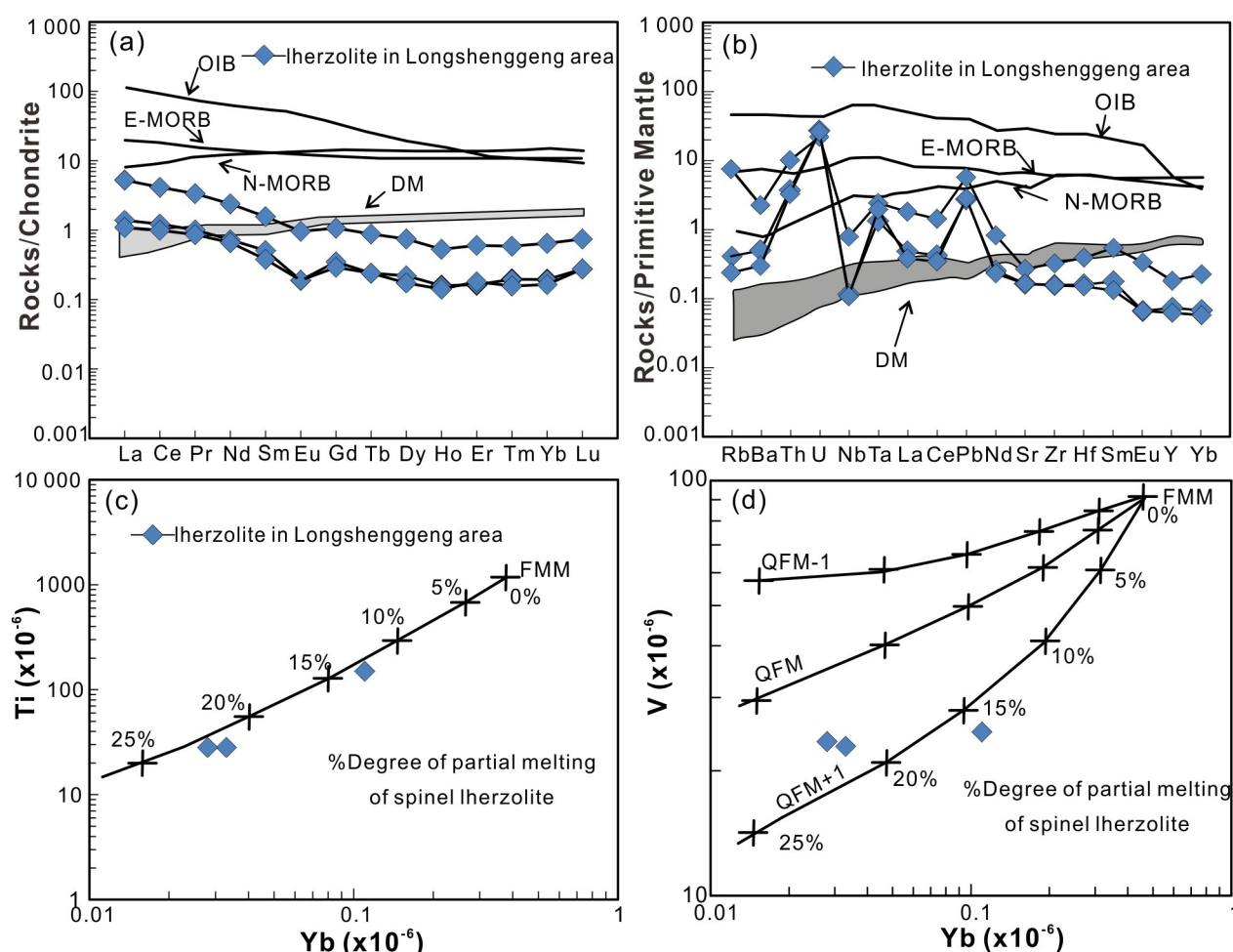


Figure 7. (a) Chondrite-normalized rare earth element patterns of the studied Iherzolite; (b) primitive mantle-normalized trace element spidergram of the studied Iherzolite; (c) plot of Yb versus Ti; (d) plot of Yb versus V for the Iherzolite from the Longshenggeng area in the East-Kunlun tectonic belt. Chondrite and primitive mantle values for normalization are from Boynton (1984) and Sun and McDonough (1989), respectively; DM data from Salters and Stracke (2004) and Workman and Hart (2005); OIB, E-MORB and N-MORB data from Sun and McDonough (1989); FMM data from Pearce and Parkinson (1993).

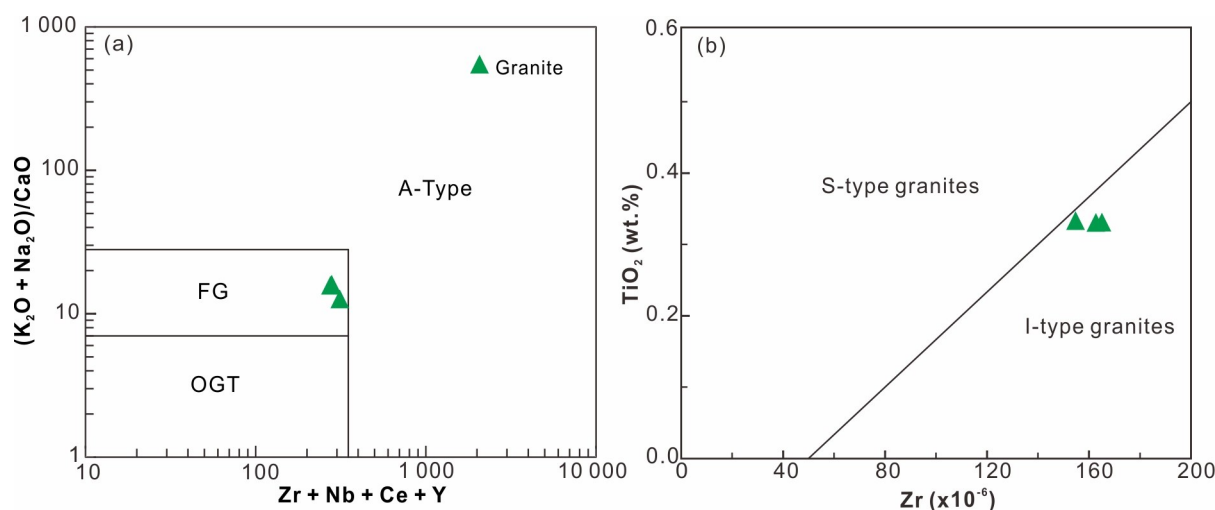


Figure 8. Classification diagram of granite types in Longshenggeng area, East Kunlun tectonic belt.

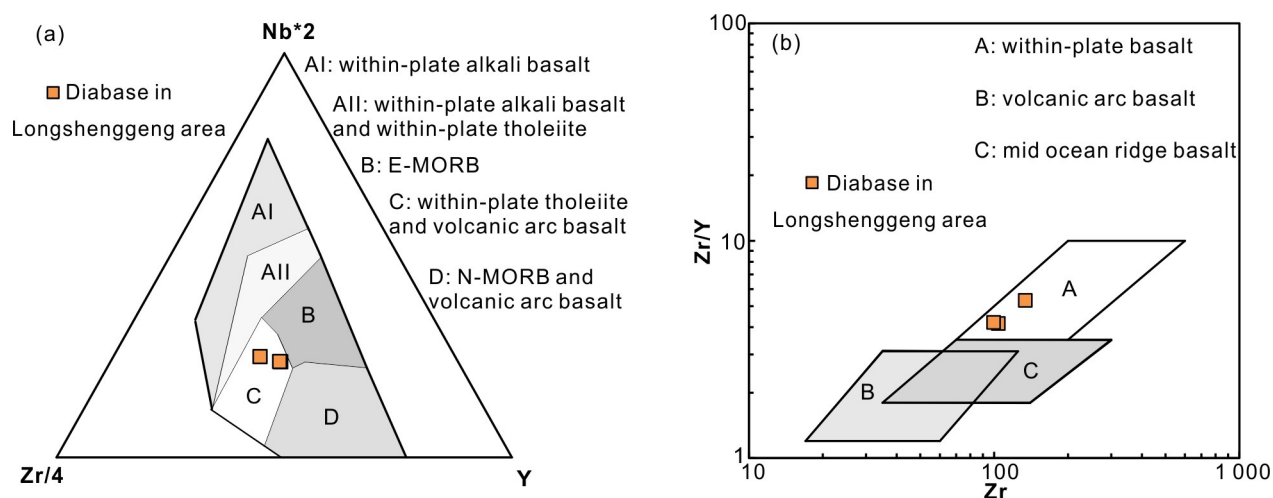


Figure 9. Nb*2-Zr/4-Y diagram (a) and Zr/Y-Zr diagram (b) of the diabase in the Longshenggeng area, East Kunlun tectonic belt (according to Meschede, 1986).

Tal Group in the area is thought to have formed around ~474–450 Ma in a back-arc basin setting at an active continental margin (Chen et al., 2013; Zhang Y L et al., 2010; Figure 10b). Based on these lines, the SSZ-type ophiolites found in the East Kunzhong belt and the contemporaneous island arc magmatism are products of the northward subduction of the main oceanic basin of the Proto-Tethys Ocean, which is depicted by the Buqingshan-Animaqing ophiolite mélange belt. The subduction process led to the formation of an active continental margin with a trench-arc-basin system in the East Kunzhong region.

During the Late Silurian, the subduction and consumption of the Proto-Tethys Ocean were completed, leading to the amalgamation of the East Kunlun Block with the Bayan Har Block to the south, marking the conclusion of the Early Paleozoic tectonic cycle. By the Carboniferous, the East Kunlun region transitioned into the evolutionary stage associated with the Paleo-Tethys Ocean. The opening of the Animaqing Ocean, a branch of the Paleo-Tethys Ocean, is indicated by the presence

of the Derni and Harguole ophiolites of 345–333 Ma exposed in the southern Kunlun region (Chen, 2018). However, from 330 to 260 Ma, the East Kunlun region did not produce subduction-related volcanic arc magmatic activity, possibly indicating that subduction had not yet started during this period (Chen, 2018). Subsequently, island arc magmatism developed extensively during the Late Permian to Middle Triassic, as evidenced by the 252–241 Ma granodiorite-quartz diorite in the Balong area, the 259 Ma granodiorite in the Wulongou area, the 258–252 Ma granite-granodiorite in the Hallagatu area, the 253 Ma lamprophyre in the Yuejinshan area, the 251–249 Ma Bairiqili complex, and the 242–237 Ma Gouli mafic rocks (Chen, 2018). Most studies suggest that this island arc magmatism was a product of the northward subduction of the Paleo-Tethys Ocean beneath the East Kunlun Block. However, there is still debate regarding the closure time of the Paleo-Tethys Ocean, with most estimates placing it around 250 to 240 Ma (Wu et al., 2020; Figure 10c). The petrochemical characteristics of the diabase suggest that it formed by partial melting of the asthenosphere mantle

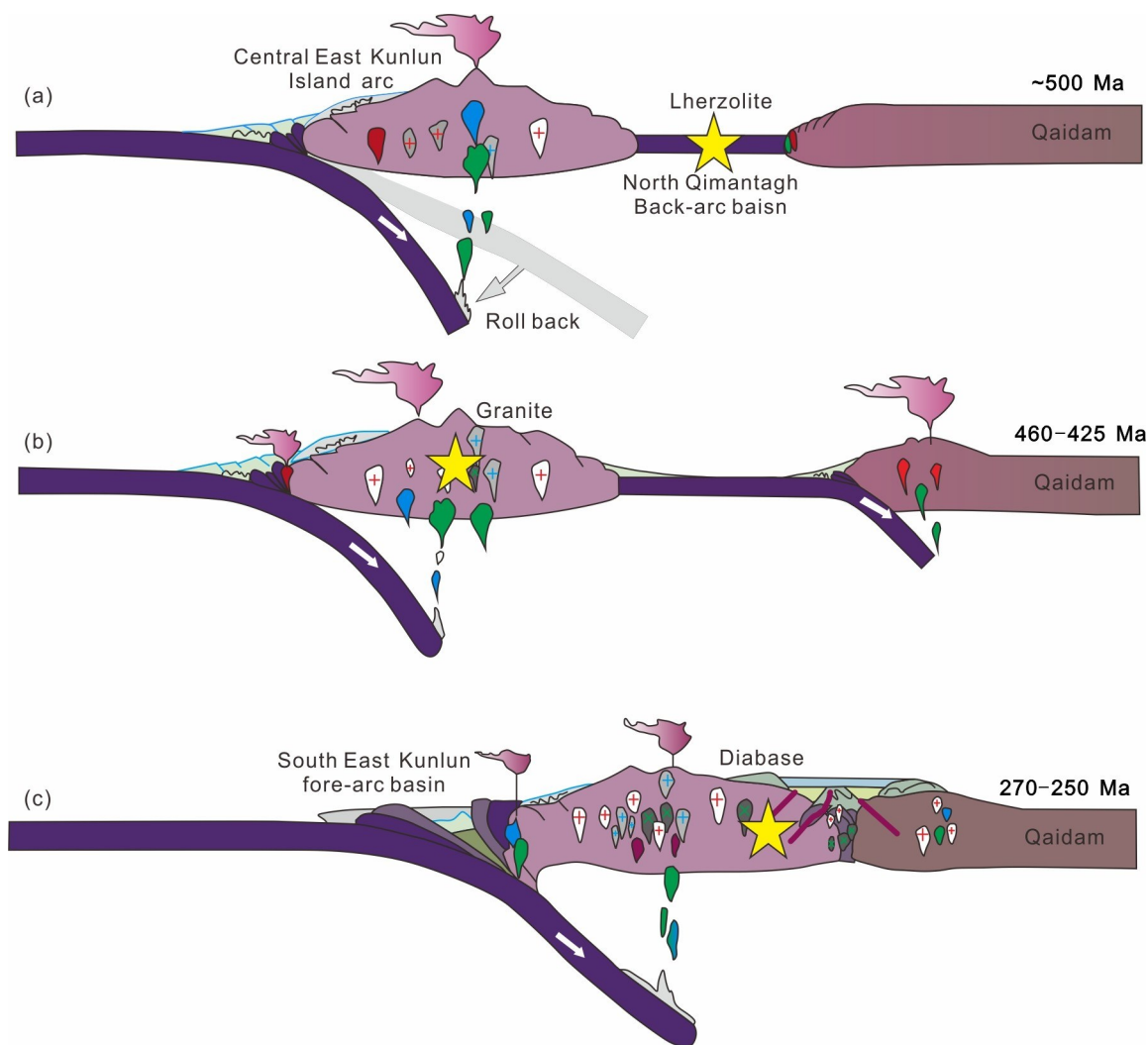


Figure 10. Tectonic evolution in the east part of the East-Kunlun tectonic belt.

in a within-plate setting. However, the formation age of the diabase in this study was determined to be 260 ± 14 Ma with significant analytical error. Thus, a more precise determination of the crystallization age of the diabase in the future studies will help better constrain the exact closure time of the Paleo-Tethys Ocean. Additionally, the diabase studied may have formed during the transition from subduction to post-collisional extension.

5 CONCLUSIONS

(1) A suite of mafic-ultramafic and granitic rocks was discovered in the Longshenggeng area of the East Kunlun region. Apatite U-Pb dating results indicate that the lherzolite, granite and diabase have ages of 492 ± 5 , 473 ± 6 , and 260 ± 14 Ma, respectively.

(2) The studied intrusive rocks in the Longshenggeng area originate from different magmatic sources. The 492 Ma lherzolite is part of SSZ-type ophiolites formed above the subduction zone; the 473 Ma granite formed at an active continental margin under an oceanic-continent subduction setting; and the 260 Ma diabase was formed by partial melting of the asthenosphere mantle in a within-plate setting at shallow depths.

(3) The lherzolite in the Longshenggeng area is part of the East Kunzhong ophiolite mélange belt, representing fragments of a back-arc basin formed by the northward subduction and consumption of the main oceanic basin of the Proto-Tethys Ocean. The ~20 Ma younger granite represents island arc magmatic products formed during the northward subduction of the Proto-Tethys Ocean. In contrast, the diabase studied may have formed during the transition from subduction to post-collisional extension.

ACKNOWLEDGMENTS

This work was supported by the Qinghai Provincial Special Fund for Geological Exploration-Deep Mineral Exploration Breakthrough Demonstration Project in Key Ore Concentration Areas of Qinghai Province (No. 2023085029ky004), New Round of National Strategic Action for Mineral Exploration Breakthrough-Research and Demonstration of Air-Ground Collaborative Efficient Technologies for Copper-Nickel Sulfide Deposits in the East Kunlun Plateau Desert Region (No. ZKKJ202416), National Key R&D Program of China-Novel Geochemical Exploration Technologies for Desert Gobi and Alpine

Grassland Shallow Overburden Terrains (No. 2024ZD100 2403), Kunlun Talent Program of Qinghai Province jointly support. We especially thank Jinyu Li, Jiaqi Liang, and Wenzhe Zhao for their help with data processing. The final publication is available at Springer via <https://doi.org/10.1007/s12583-024-0076-2>.

Electronic Supplementary Materials: Supplementary materials (Tables S1–S2) are available in the online version of this article at <https://doi.org/10.1007/s12583-024-0076-2>.

Conflict of Interest

The authors declare that they have no conflict of interest.

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