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Article

Chronology and Geochemistry of Intrusive Magmatic Rocks in the Shiquanhe Ophiolitic Mélange, Tibet: Constraints on the Tectonic Evolution of the Meso-Tethys Ocean

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Abstract

The magmatic activity is crucial for identify the tectonic framework of ancient ocean. In this study, a systematically work including field survey, zircon LA-ICP-MS U-Pb dating, and whole-rock geochemical analysis is carried on to investigated the intrusive magmatic rocks of quartz diorite and granodiorite within the Meso-Tethyan Shiquanhe Ophiolitic Mélange (SQM), Tibet. Zircon U-Pb dating yields the weighted mean ages of 174.7 ± 1.4 Ma (quartz diorite) and 178.9 ± 1.2 Ma (granodiorite) respectively, indicating the Early Jurassic formation age. The quartz diorite is metaluminous ($A/NKC = 0.77-0.95$), while the granodiorite is weakly peraluminous ($A/NKC = 0.95-1.21$), and both of them exhibit tholeiitic–calc-alkaline geochemical characteristics and classified as I-type granites. The right-dipping rare earth element (REE) patterns, enrichment in large ion lithophile elements (LILEs: Rb, Ba, Th), and depletion in high field strength elements (HFSEs: Nb, Ta, Ti), as well as relatively high $(La/Yb)_N$ ratios represent the island arc TTG-like magmatism origin. Combine with the previous works, we suggest the Shiquanhe opiolitic mélange represent an island arc and back-arc assemblage rather than an independent ocean basin. Meanwhile, this Early Jurassic island arc magmatism initiated a new era of the Mesozoic mineralization in Shiquanhe area.

Keywords: quartz diorite; granodiorite; zircon U-Pb age; geochemistry; Shiquanhe ophiolite; Meso-Tethy ocean

1. Introduction

As a global Paleo-ocean system between the Gondwana and Laurasia supercontinents during the Phanerozoic [1,2], the Tethyan tectonic domain serves a natural laboratory for deciphering the mechanisms of ocean-continent transition, plates interaction, and continental growth, and has been focused by many researchers for years [3–7]. Suture zones and associated ophiolites in the Tibetan

Plateau provide a record for over 500 million years of Tethyan tectonic evolution, which include the Proto-Tethyan West Kunlun suture, Paleo-Tethyan Kunlun, Jinsha and Shuanghu sutures, Meso-Tethyan Bangong suture, and Neo-Tethyan Yarlung-Zangbo suture [1,8]. They provide crucial evidence for reconstructing the tectonic evolution of ancient oceans. Among them, the Shiquanhe-Namtso Ophiolitic Mélange Zone (SNMZ) and Bangong-Nujiang Suture Zone (BNSZ) which separate the Qiangtang terrane to the north and the Lhasa terrane to the south represent the remnants of the Meso-Tethyan ocean [1,9]. Their tectonic setting and affinity holds important significance for recovery the Meso-Tethys framework and Tibet evolution, as well as the regional mineralization, but there are still remain some controversies [10–16].

The Shiquanhe-Namtso Ophiolitic Mélange Zone, although has been discovered for a long time, but still has relatively lower research degree than Bangong-Nujiang Suture Zone. Several hypotheses were proposed about its tectonic nature, such as: 1) the southward tectonic nappe of the Bangong-Nujiang Suture Zone [10,12,17,18]; 2) the island arc and back-arc basin system formed by the subduction of the Bangong Meso-Tethys [13,19–23]; 3) the remnants of an independent oceanic crust [24,25]. The intrusive magmatic rocks are important components of SNMZ, and it could provide important spatial and temporal informations besides the volcanic rocks. But the relevant research a seldom so far.

The Shiquanhe Ophiolitic Mélange (SOM) is located at the west end of the SNMZ (Figure 1) and plays an important role in terms of the tectonic evolution of this mélange zone. In this contribution, we systematically collected representative intrusive rocks samples within the Shiquanhe Ophiolitic Mélange by detail field surveys. Through the analyses of spatial distribution and contact relation with country rocks, petrographic classification, whole-rock geochemical analysis, and zircon U-Pb chronological dating, this study aims to clarify the formation age, petrogenesis, tectonic setting of these intrusive rocks, and further more to discuss its implications for the tectonic framework of the Shiquanhe Ophiolitic Mélange with Bangong Suture.

2. Geological Background and Sample Locations

From north to south, the Tibetan Plateau is divided into several major parts by the Jinsha suture zone (JSSZ), Longmu-Shuanghu suture zone (LSSZ), BNSZ, SNMZ, and Indus-Yarlung Tsangpo suture zones (IYTSZ), including the Songpan-Ganzi, Northern Qiangtang (NQ), Southern Qiangtang (SQ), Lhasa, and Himalaya terranes (Figure 1a) [26–32]. The BNSZ begins from the Bangong Lake (at the western end), passing through the Gerze, Dongqiao, Amdo, Dingqing, and terminates east to the Nujiang ophiolite. The SNMZ begins in the Shiquanhe (at the western end), passing through the Asa, Yongzhu, Namu Tso, Jiali and extends east to Bomi ophiolite (Figure 1b) [31,33].

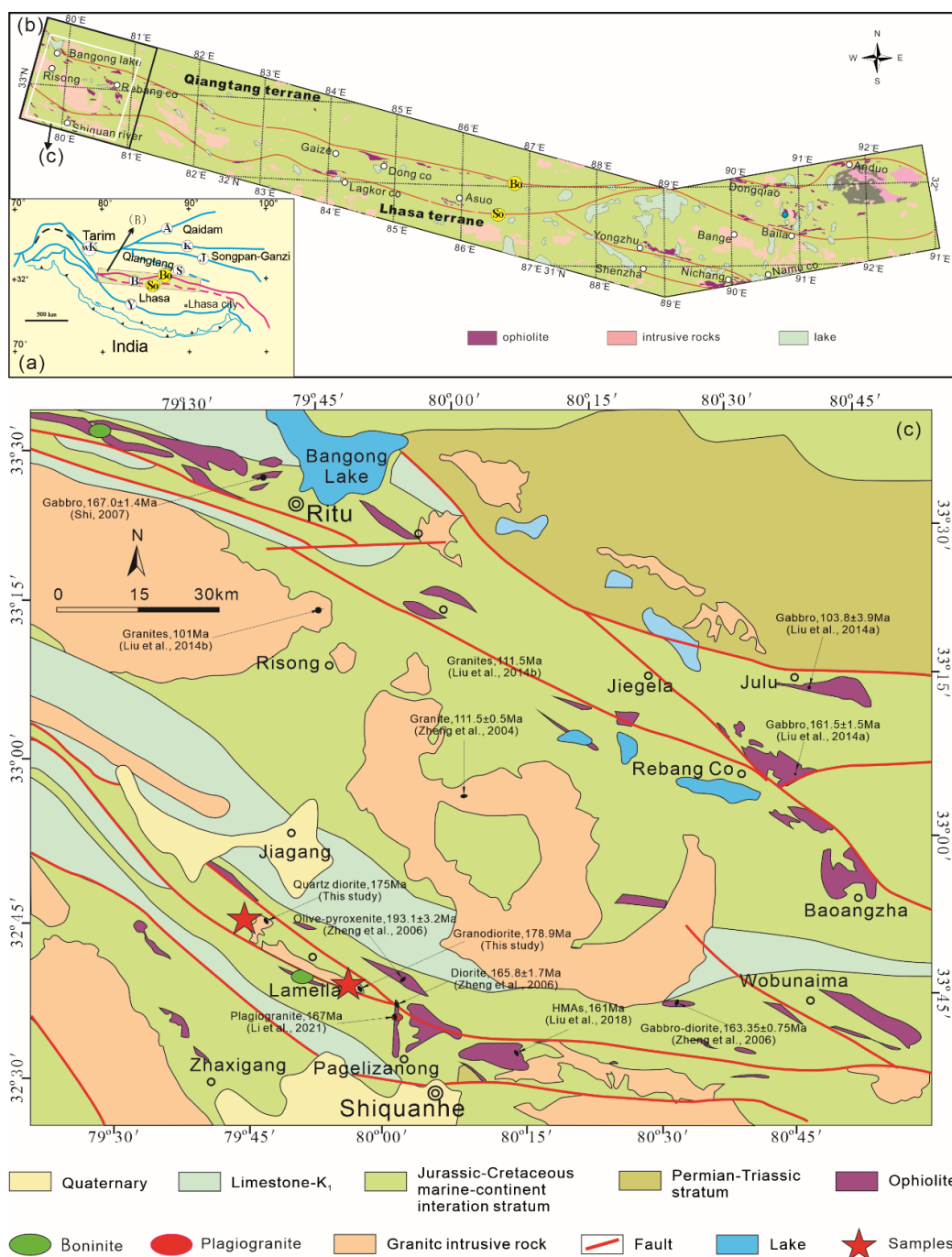


Figure 1. (a) Tectonic map of the Tibetan Plateau. Main sutures and faults: wK-west Kunlun suture, A-Altyan fault zone, K-Kunlun suture, J-Jinsa suture, S-Shuanghu suture, B-Bangong suture, Bo-Bangong-Nuijiang ophiolite sub-belt, So-Shiquanhe-Jiali ophiolite sub-belt, Y-Yarlung Zangbo suture, After Zhang et al. [35] and Xin et al. [36]. (b) Simplified geological map showing the distinct geological constitute of middle to western Bangong suture and adjacent terrane. Bo: The Bangong Lake-Nuijiang ophiolite sub-belt (BNO sub-belt) in the north (the BNSZ in a strict sense), So: Shiquanhe-Jiali ophiolite sub-belt (SJO sub-belt) in the south (the SNMZ in a strict sense), after [37]. (c) Geological map of the Bangong Lake-Shiquanhe area, western BSZ (after Zheng et al. [38] and our field work).

The selected study area is located in the Shiquanhe area near the Shiquanhe Town (Figure 1b). As the largest exposed ophiolitic section in the west part of SNMZ, the ophiolitic mélanges in this region generally extend in a northwest direction, spanning over 60 kilometers [22,30,34]. The diorite intrusions studied in this paper are exposed in the Banglongchamu and Qionggaleniao areas of the Shiquanhe region and mainly intruded into the Shiquanhe Ophiolitic Mélange as stocks and bosses

(Figures 1c and 2a,c). They extending in an east-west direction and have a total outcrop area of approximately 6.5 km². The primary rock types include quartz diorite, tonalite, and granodiorite.

3. Field Relations and Petrography

In the field, the granodiorite occurs primarily as lenses intruding serpentized harzburgite (Figure 2a). It shows gray-white in color and exhibits a fine-grained, granitic texture and a massive structure. Under the microscope, it is composed of plagioclase, K-feldspar, quartz, amphibole, and biotite. Plagioclase is about 4-50 vol. %. They occur as hypidiomorphic tabular crystals, with grain sizes generally 0.2-2 mm, and well-developed zoning structures as well as polysynthetic twinning. They are distributed randomly, with alterations of kaolinization and sericitization. K-feldspar is about 5-10 vol. %. They occur as anhedral granular crystals, mainly microcline, with grain sizes typically 0.5-3.5 mm. They are distributed interstitially, with slight kaolinization, and perthitic twinning is visible. Quartz is about 20-25 vol. %. They occur as anhedral granular crystals, with grain sizes usually 2-6 mm. They are distributed interstitially, with obvious recrystallization and local grain refinement at the edges. Distinct undulatory extinction is present within grains. Amphibole is approximately 5 vol. %. They occur as hypidiomorphic-anhedral prismatic or prism-granular crystals, with grain sizes 0.2-2 mm and some grains form pseudomorphs. They are distributed randomly, with alterations such as uralitization and chloritization. Biotite is about 5-10 vol. %. They occur as flaky crystals, with flake diameters generally 0.2-2 mm. They are distributed randomly, and most grains are replaced by chlorite, muscovite, or epidote to form pseudomorphs, with titanium minerals precipitated. The accessory minerals mainly include zircon and apatite (Figure 2b).

The quartz diorite is primarily gray to light-gray in color. It occurs as lenses intruding into gabbroic complex (Figure 2c) and exhibits a medium- to fine-grained, subhedral granular texture and a massive structure. Under the microscope, it is composed of plagioclase, quartz, amphibole, and pyroxene. Plagioclase accounts for about 50-60 vol. %. They occur as hypidiomorphic tabular crystals, with visible zoning structure, and polysynthetic twinning is common. The grain sizes ranging from 0.2 to 2 mm with a slight directional arrangement of long axes. They distributed randomly with alterations such as sericitization, kaolinization, and epidotization. Quartz is approximately 10 vol. %. They occur as anhedral granular crystals, with grain sizes typically 1-5.5 mm. They are distributed interstitially, with undulatory extinction observed within grains. Amphibole is about 20 vol. %. They occurs as hypidiomorphic prismatic or prism-granular crystals, with grain sizes mostly 0.2-2 mm (a few reaching 2-3.5 mm). They are distributed randomly, and aggregates exhibit a banded or striped appearance with slight orientation. A small number of grains are replaced by uralite, chlorite, or epidote. The accessory minerals mainly include magnetite and epidote (Figure 2d).

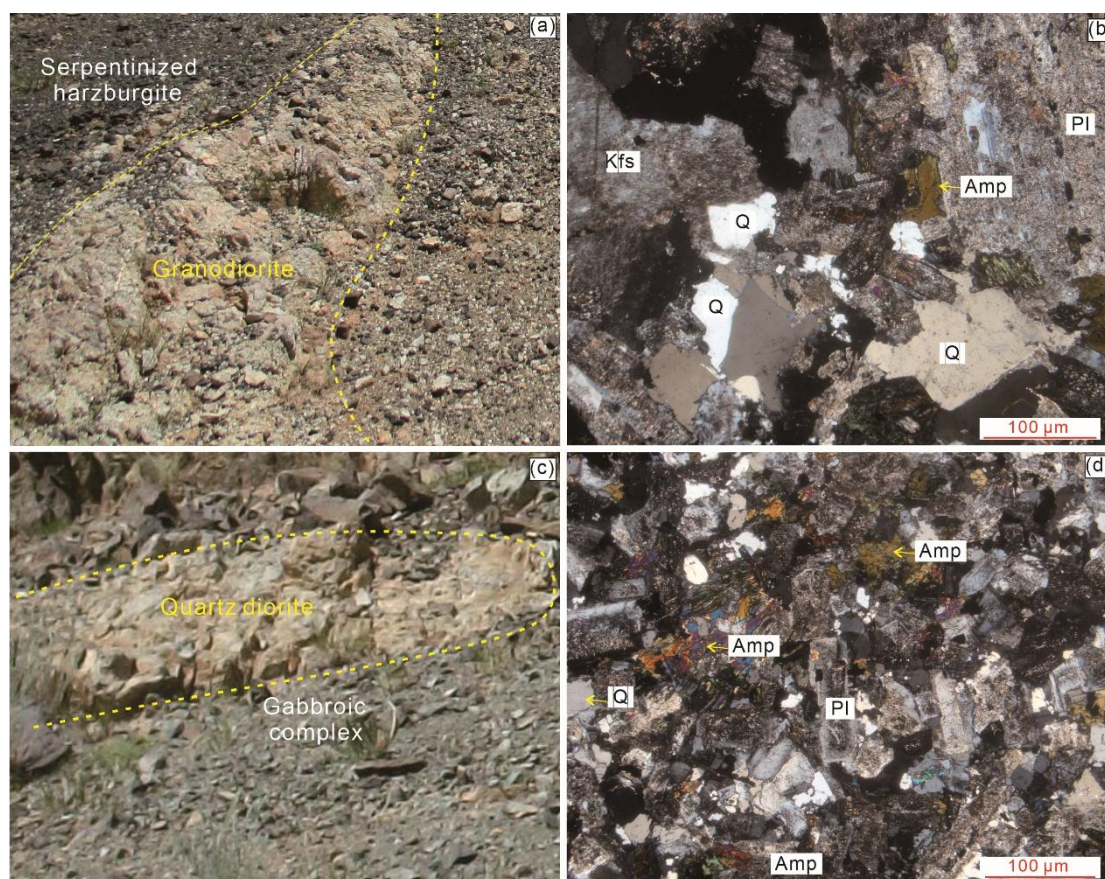


Figure 2. Field occurrences of the quartz diorite (a) and granodiorite (c), photomicrographs showing quartz diorite (b) and granodiorite (d). Amp = amphibole; Pl = plagioclase; Kfs = K-feldspar.

4. Analytical Methods

4.1. Zircon U-Pb Geochronology

Two diorite samples (PM204TW1, quartz diorite and PM207TW1, granodiorite) were collected for zircon U-Pb analysis. Zircons were first separated from the samples by heavy-liquid and magnetic techniques. Cathodoluminescence (CL) images were subsequently used to select positions for U-Pb dating. U-Pb geochronology of zircon was conducted by LA-ICP-MS at Nanjing FocuMS Technology Co. Ltd. A 193 nm ArF-excimer laser ablation coupled with an Agilent 7500a Inductively Coupled Plasma Mass Spectrometer (LA-ICP-MS) was used to determine the U-Pb isotopic compositions, and the detailed procedures follow the description of [39]. 91500 (1062 Ma) was used as external standard to correct instrumental mass discrimination and elemental fractionation during the ablation. GJ-1 (600 Ma) and Plešovice (337 Ma) were treated as quality control for geochronology. Raw data reduction was performed off-line by ICPMSDataCal software [37]. Isoplot/Ex_ver3 was used to make weighted mean age calculations and concordia diagrams [40].

4.2. Major and Trace Elements Analyses

Five granodiorite and three quartz diorite samples were collected from fresh outcrops in Shiquanhe area. The major elemental composition analysis was done by using a PAN analytical Axios X-ray fluorescence (XRF) spectrometer at ALS Chemex Company, Guangzhou, China and trace element composition analysis was determined by using PE ELAN 6000 ICP-MS at Nanjing FocuMS Technology Co. Ltd. The samples were crushed into small chips, and the secondary vein materials, amygdaloids and weathered rims were identified and discarded by using a binocular microscope. The rock chips were picked, ultrasonically cleaned in 4N hydrochloric acid for 30 minutes, and then powdered to <200 mesh granule size in an agate ring mill after drying. Details of the major and trace

element composition analysis procedures follow the description of Chen et al. [41] and Qi and Grégoire [42], respectively. The precision for the major element analysis is better than $\pm 1\text{-}2\%$ for concentration of 0.5 wt.% and for the trace elements precisions is better than $\pm 5\%$.

5. Results

5.1. Zircon U-Pb Geochronology

The results of zircon U-Pb dating analysis from the granodiorite and quartz diorite in supplementary Tables S1. In the cathodoluminescence (CL) images (Figure 3a), the analysed zircon grains from the quartz diorite sample (PM204TW1) range in length from 60 to a few hundred microns and have sharp and clear edges. In addition, all of them exhibit oscillatory zoning, which are characteristic features of zircons that crystallized from magmas [43]. For the granodiorite sample (PM207TW1), the zircon grains are mainly acicular and prismatic with clear edges and corners (Figure 3b). Besides, these zircons exhibit distinct oscillatory zoning (Figure 3b), which is consistent with the characteristics of zircons from acidic magma [43]. Their Th/U ratios (0.27-0.59, PM204TW1; 0.36-0.58, PM207TW1, respectively) were higher than those of metamorphic zircons (Supplementary Table S1). All these observations are consistent with characteristics of the magmatic zircons [44].

For quartz diorite sample PM204TW1, 18 spots were analyzed on 18 zircons, all of which yielded relatively concordant ages. The $^{236}\text{Pb}/^{238}\text{U}$ ages of the concordant spots are continuously distributed between 171 ± 4 Ma and 179 ± 4 Ma, yielding a weighted mean age of 174.7 ± 1.4 (Mean Square of Weighted Deviates, MSWD = 0.39) and a concordia age of 174.3 ± 1.7 Ma (MSWD = 0.45) (Figure 3a). 31 measurement points were analyzed on 31 zircon grains, and 31 concordant ages were obtained for granodiorite sample PM207TW1. The zircon $^{236}\text{Pb}/^{238}\text{U}$ ages of these 31 concordant spots range from 172 ± 6 Ma to 193 ± 7 Ma, yielding a weighted mean age of 178.9 ± 1.2 Ma (MSWD = 2.6) and a concordia age of 180.1 ± 1.6 Ma (MSWD = 0.97) (Figure 3b).

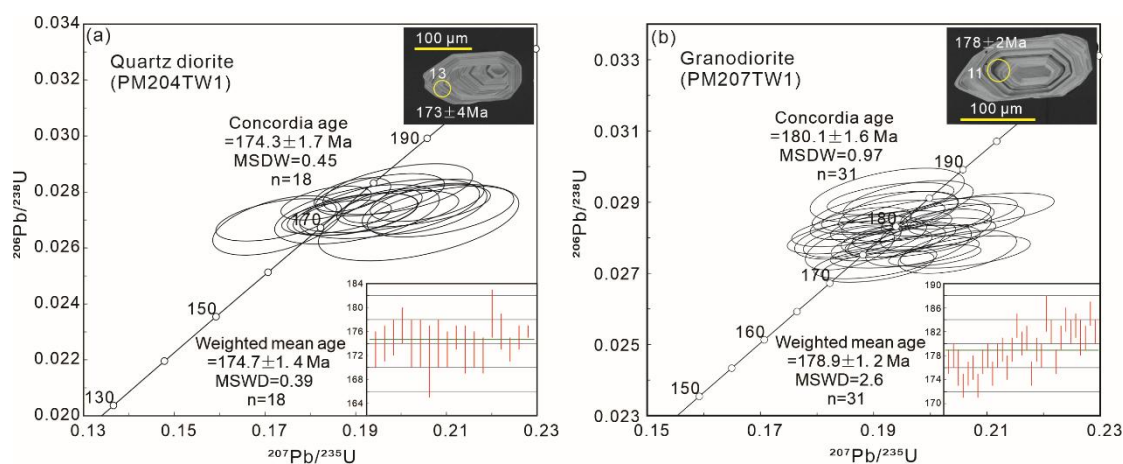


Figure 3. Concordia plots and weighed average age of LA-ICP-MS U-Pb data of quartz diorite (a) and granodiorite (b), analysed zircon CL images in the quartz diorite (c) and granodiorite (d).

5.2. Whole-Rock Major and Trace Elements

5.2.1. Quartz Diorite

The SiO_2 content ranges from 55.49 wt. % to 61.66 wt. %, with an average of 58.49 wt. %, belonging to intermediate rocks. However, based on their microscopic features (such as the presence of abundant quartz), they could be classified as quartz diorite. Their contents of K_2O and P_2O_5 are 0.42-0.80 wt. % and 0.06-0.08 wt. %, respectively. Besides, they have high MgO and Fe_2O_3 content (3.45-5.68 wt. % and 7.08-10.24 wt. %) (Supplementary Table S2). Their differentiation index (DI) ranges from 39.18 to 48.96 (average: 42.93), and the solidification index (SI) ranges from 26.15 to 30.32

(average: 28.82), indicating a low degree of magma differentiation. The alkalinity rate (σ) ranges from 0.44 to 0.95 (average: 0.64), indicating the calcic series. The aluminum saturation index (A/NKC) ranges from 0.77 to 0.95 (average: 0.87), and the A/NK ratio ranges from 2.72 to 3.69 (average: 3.22), belonging to the metaluminous rocks.

In the total alkali-silica (TAS) diagram [45] (Figure 4a), the samples belong to the subalkaline series. In the normative mineral An-Ab-Or diagram [46] (Figure 4b), the samples plot in the tonalite field, which is consistent with the microscopic identification as quartz diorite. When further plotted in the F-A-M classification diagram [47] (Figure 4c), the samples fall into the calc-alkaline series field. In the K_2O - SiO_2 variation diagram [48] (Figure 4d), two samples fall into the low-K (tholeiitic) series field and other samples dropped into the calc-alkaline series field, indicating the low potassium characteristics.

The total REE content (ΣREE) of the quartz diorite samples range from 25.53 to 29.66 ppm, with an average of 27.43 ppm, indicating a low total REE content (Supplementary Table S2). The $\Sigma LREE/\Sigma HREE$ ranges from 2.29 to 3.42, with an average of 2.99, indicating insignificant LREE-HREE fractionation. The Eu anomaly (δEu) ranges from 1.15 to 1.34, with an average of 1.26, showing weak Eu enrichment, indicating the mantle-derived magma source. The Ce anomaly (δCe) ranges from 0.96 to 1.02, with an average of 0.99, showing without obvious Ce depletion or enrichment. The chondrite-normalized ratios are as follows: $(La/Yb)_N = 1.34$ -2.58 (average: 2.14), $(Ce/Yb)_N = 1.23$ -2.07 (average: 1.73), and $(Gd/Yb)_N = 0.64$ -0.78 (average: 0.72). All these values indicate a weak LREE enrichment and insignificant REE fractionation. The REE distribution pattern curve is a nearly horizontal smooth curve (Figure 5a).

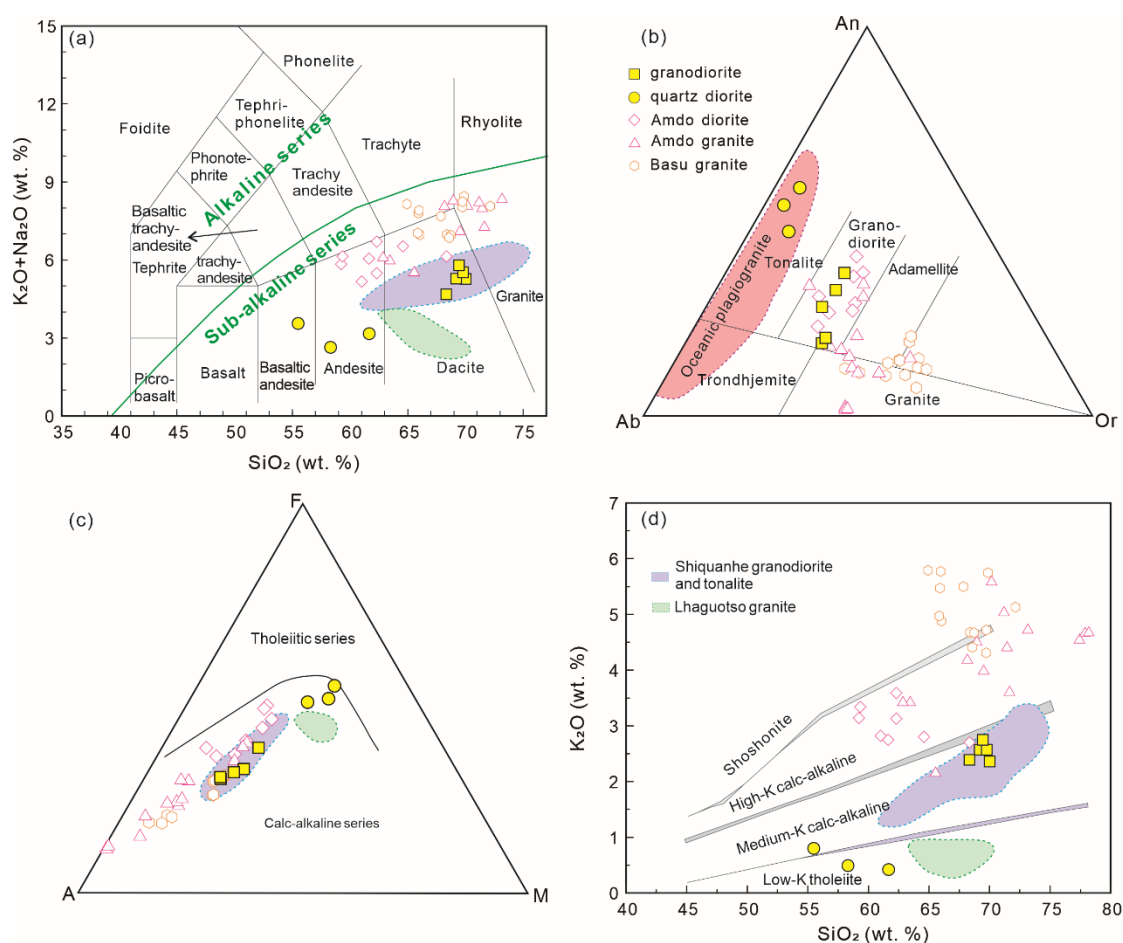


Figure 4. (a) K_2O+Na_2O vs. SiO_2 (modified after [45]) (b) An-Ab-Or (modified after [46]), (c) F-A-M (modified after [47]), and (d) SiO_2 vs. K_2O diagrams (modified after [48]) for the Shiquanhe granodiorite and quartz diorite. Data sources for comparison: Amdo granite and diorite [14], Basu granite [49], Shiquanhe granodiorite and tonalite [50], and Lhaguotso granite [50].

Among the quartz diorite samples, the contents of Cs, Sc, and V are 1.24-4.05 ppm, 19.8-249 ppm, and 185-287 ppm, respectively. The Rb/Sr ratio of the quartz diorite samples ranges from 0.03 to 0.12 (average: 0.09), indicating a crust-mantle mixed magma source. The other trace element ratios are as follows: Rb/Ba = 0.07-0.14 (average: 0.10), K/Rb = 189.54-273.52 (average: 228.81), Zr/Hf = 37.63-41.87 (average: 39.85), and Nb/Ta = 3.98-15.74 (average: 8.6). In the trace element spider diagram (Figure 5b), large ion lithophile elements (LILEs) such as K, Rb, Sr, and Ba are relatively enriched, while high field strength elements (HFSEs) are relatively depleted, with obvious Nb depletion. Compared with the spider diagram proposed by [51], the samples show the normal arc granite characteristics .

5.2.2. Granodiorite

The SiO₂ content of the granodiorite ranges from 68.72 wt. % to 70.02 wt. %, with an average of 69.25%, belonging to acid rocks. Meanwhile, based on their microscopic features (such as the presence of abundant quartz and amphibole), they could be classified as granodiorite. Compared to the quartz diorite, the granodiorite samples have lower MgO (1.65-2.45 wt. %) and Fe₂O₃ (3.20-4.70 wt. %) content and higher content of K₂O and P₂O₅ (2.36-2.75 wt.% and 0.08-0.10 wt. %, respectively) (Supplementary Table S2). Their differentiation index (DI) ranges from 65.56 to 75.43 (average: 71.43), and the solidification index (SI) ranges from 16.65 to 21.38 (average: 19.1), indicating a moderate degree of magma differentiation. The alkalinity rate (σ) ranges from 0.7 to 1.25 (average: 1.0), belonging to the calcic series. The aluminum saturation index (A/NKC) ranges from 0.95 to 1.21 (average: 1.06), and the A/NK ratio ranges from 1.77 to 2.28 (average: 1.96), indicating weakly peraluminous rocks. In the CIPW normative minerals, the corundum (C) content ranges from 0 to 2.55 wt. %: 2 samples have C < 1 wt. %, and 3 samples have C > 1 wt. %, with an average of 1.02 wt. %. In the normative mineral An-Ab-Or diagram (Figure 4), most samples plot in the granodiorite field, which is consistent with the microscopic identification. In the total alkali-silica (TAS) diagram (Figure 4a), the samples are classified as the subalkaline series. When further discriminate by the F-A-M classification diagram (Figure 4c), the granodiorite samples also fall into the calc-alkaline series field, which is consistent with the calc-alkaline characteristics they display in the K₂O-SiO₂ diagram (Figure 4d).

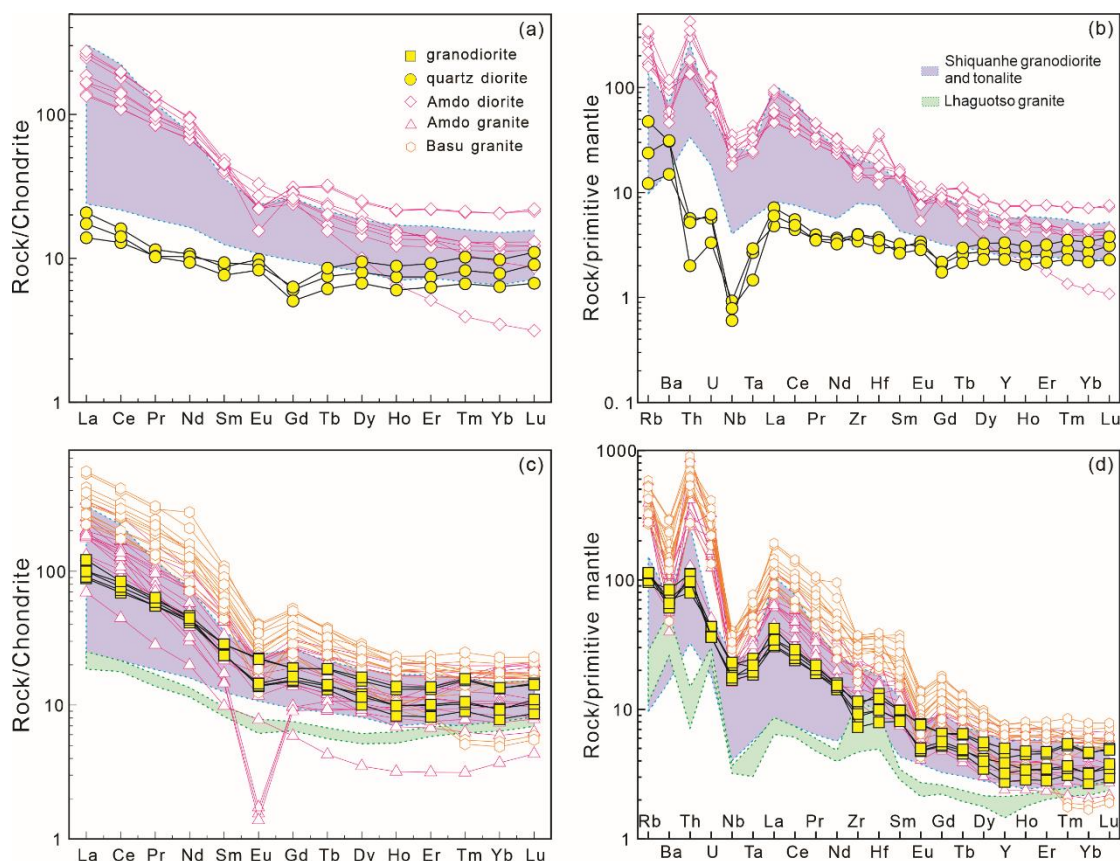


Figure 5. Chondrite-normalized REE patterns (a and c) and primitive-mantle-normalized spider diagrams (b and d) for the Shiquanhe granodiorite and quartz diorite. Values of chondrite, primitive mantle, N-MORB (normal mid-ocean ridge basalt) are from [52]. Data sources: Amdo granite and diorite [14], Basu granite [49], Shiquanhe granodiorite and tonalite [50], and Lhaguotso granite [50].

The total REE content (ΣREE) is relative low and ranges from 104.35 to 122.65 ppm, with an average of 113.16 ppm. The $\Sigma\text{LREE}/\Sigma\text{HREE}$ ranges from 6.41 to 9.97, with an average of 8.27, showing significant LREE-HREE fractionation. The Eu anomaly (δEu) ranges from 0.706 to 1.036, with an average of 0.84 and the Ce anomaly (δCe) ranges from 0.88 to 0.98, with an average of 0.93, indicating the depletion of Eu and Ce. The chondrite-normalized ratios are as follows: $(\text{La}/\text{Yb})\text{N} = 6.20\text{--}12.40$ (average: 9.03), $(\text{Ce}/\text{Yb})\text{N} = 4.8\text{--}8.49$ (average: 6.78), and $(\text{Gd}/\text{Yb})\text{N} = 1.37\text{--}1.89$ (average: 1.58). These values indicate LREE enrichment and significant REE fractionation, which also displayed in the right-dipping distribution patterns (Figure 5).

6. Discussion

6.1. Formation Ages of the Quartz Diorite and Granodiorite

Through detailed field geological surveys, it was obviously that the granodiorite samples of this study intrude into the Jurassic ophiolitic harzburgite, and the quartz diorite intrudes into Jurassic ophiolitic gabbro complexes. This can thus constrain the intrude age is contemporary with the Jurassic ophiolite or later. The zircon U-Pb dating of this study obtain the weighted mean ages of 174.7 ± 1.4 Ma and 178.9 ± 1.2 Ma for quartz diorite and granodiorite samples respectively (Figure 3a-b). So we can conclude that these intrusive rocks formed in Early Jurassic time. Furthermore, These ages are contemporary with the newly obtained forearc setting ophiolitic gabbros in north of Lameila [23] which is nearby with our sample location, considering the two samples of granodiorite and quartz diorite are all derived from the Shiquanhe ophiolitic mélange, so we suggest there are ocean crust evaluation associated Early Jurassic magmatic events occurred in the Shiquanhe area.

6.2. Petrogenesis

6.2.1. Influence of Alteration

To investigate the petrogenesis of the intrusive rocks from the Shiquanhe ophiolitic mélangé, we need to estimate alteration effect on the samples. As shown in the Supplementary Table S2, the quartz diorite and granodiorite samples exhibit relatively low loss on ignition (LOI) values (1.68-2.82 wt. %), indicating that they have not been significantly affected by alteration or metamorphism. This is also consistent with their microscopic observations (Figure 2b,d). Consequently, we can use the elemental compositions and their ratios to discuss the petrogenesis and tectonic environment of these samples.

6.2.2. Petrogenesis of Quartz Diorite

In the A/CNK-A/NK diagram [53] (Figure 6a), the quartz diorites plot in the metaluminous field, which is consistent with the late Early Jurassic granitic rocks in the Lhaguotso area within the BNSZ [50]. This suggests that the quartz diorite samples in this study may have I-type granite features (i.e., formed by the partial melting of an unweathered igneous source rock), which is further supported by the (Zr+Nb+Y+Ce) vs. FeOt/MgO [54] and SiO₂ vs. P₂O₅ [50] diagrams (Figure 6b,c). Meanwhile, the high MgO and Fe₂O₃t of the Quartz diorite, which is consistent with the Lhaguotso plagiogranites, Shiquanhe High-Mg andesites [55] within the SNMZ and Archean Sanukitic rocks, post-Archean High-Mg adakites, and boninites [56–59]. These intermediate-acid rocks enriched in mafic components and are interpreted as a significant contribution of mantle-derived components to their source [50]. In addition, the low Rb/Sr and Rb/Ba ratios, lower Th contents, relatively weak light rare earth element (LREE) enrichments of the quartz diorites also support that these rocks were formed from a mantle-derived magma source. This implies that the magma for the quartz diorite samples in this study may contain a significant mafic component. In the C/MF vs. A/MF diagram [60] (Figure 6d), the quartz diorite samples fall into the field of partial melting of mafic rocks, implying that the the partial melting of mafic rock origin.

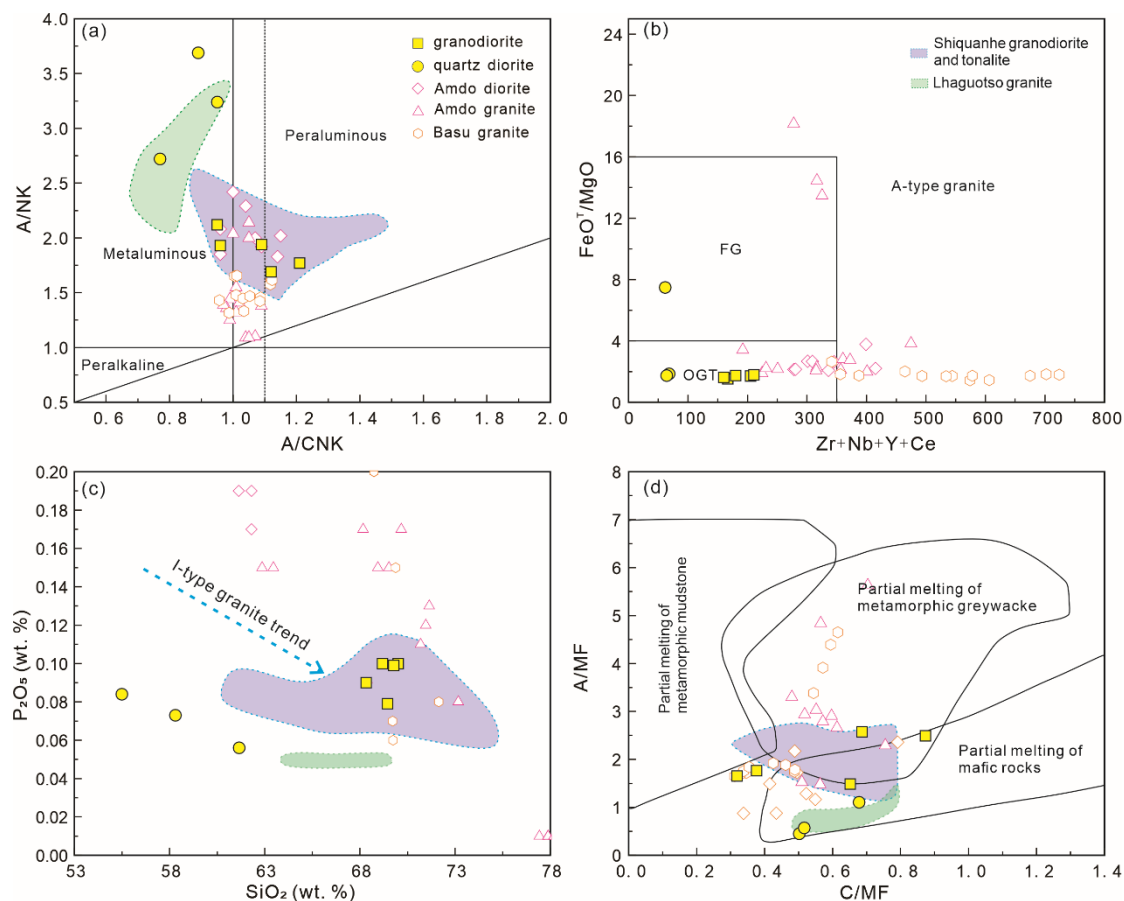


Figure 6. (a) A/CNK vs. A/NK (modified after Maniar and Piccoli [53]) (b) Zr+Nb+Y+Ce vs. FeOt/MgO, (c) A-C-F [61], and (d) C/MF vs. A/MF diagrams (modified after [48]) for the Shiquanhe granodiorite and quartz diorite. Data sources for comparison: Amdo granite and diorite [14], Basu granite [49], Shiquanhe granodiorite and tonalite [50], and Lhaguotso granite [50].

In the $\text{CaO}/(\text{FeOt}+\text{MgO}+\text{TiO}_2)$ vs. $(\text{FeOt}+\text{MgO}+\text{TiO}_2+\text{CaO})$ [62], Rb/Ba vs. Rb/Sr [63], and Th/La vs. Th [64], diagrams, the quartz diorite samples, similar to the Lhaguotso high-Mg granites within the SNMZ [50], all plot in fields close to amphibolite, metabasalt, or mid-ocean ridge basalt (MORB) (Figure 7a-c). This supports the inference of a mantle-derived source without obvious crust material input. Additionally, the quartz diorite samples in this study, analogous to the Laguocuo high-Mg granites, are characterized by low Th content and high U/Th ratios, and they both fall into the field of sediment-free island arc volcanic rocks in the U/Th vs. Th diagram [55,65] (Figure 7d). So we could conclude that the magma of the quartz diorite was derived from the melting of mantle-derived mafic rocks, without the obvious addition of crust material.

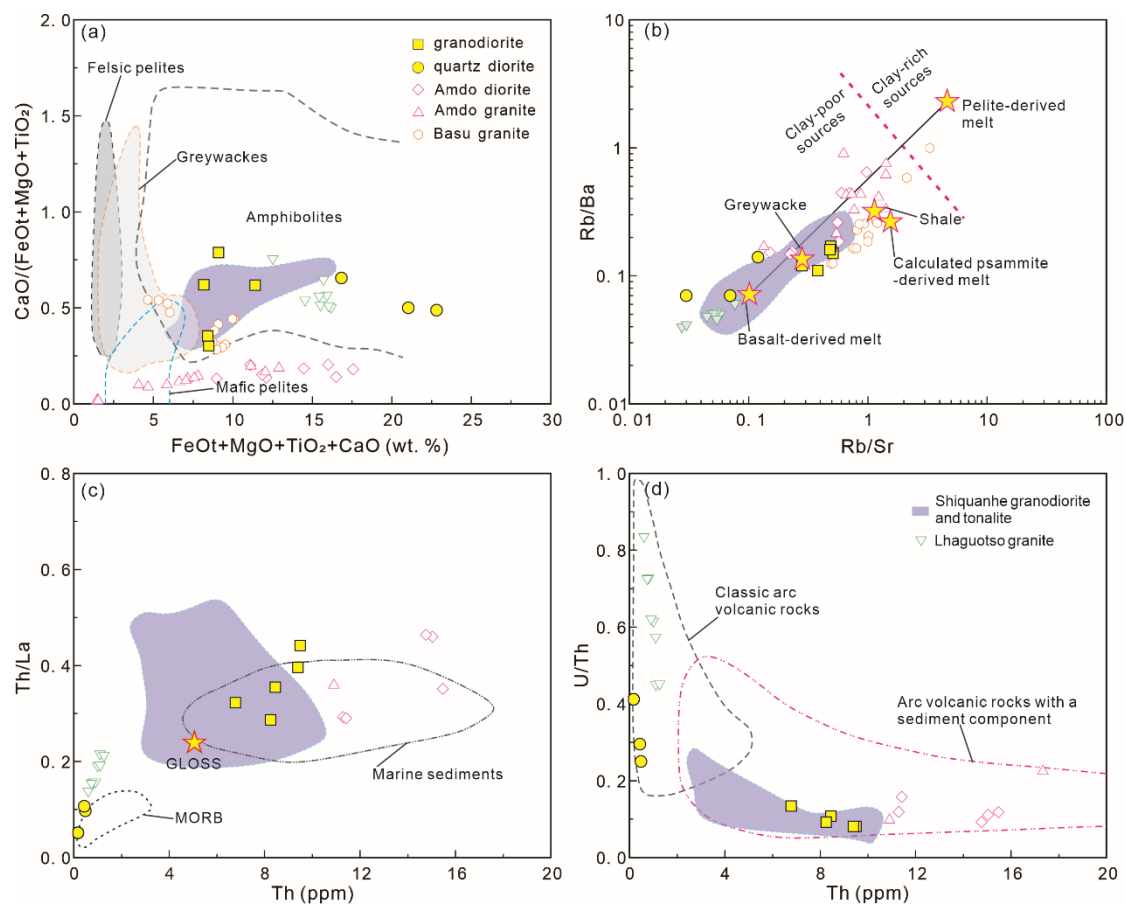


Figure 7. (a) Plots of $\text{CaO}/(\text{FeOt}+\text{MgO}+\text{TiO}_2)$ vs. $\text{FeOt}+\text{MgO}+\text{TiO}_2+\text{CaO}$ (after [62]), (b) plots of Rb/Ba vs. Rb/Sr (after [63]), (c) plots of Th/La-Th (after [64]), (d) plots of U/Th-Th (after [65]). Data sources for comparison are detailed in the Figure 6.

6.2.3. Petrogenesis of Granodiorite

As discussed in the Section 5.2, the granodiorites have higher SiO_2 , K_2O , P_2O_5 , and lower MgO and Fe_2O_3 than quartz diorites. This implies that the magma properties of the granodiorites may be different from those of the quartz diorites. Meanwhile, the granodiorites have higher A/CNK values than the quartz diorites as shown in Figure 6a. They plot within the field of previously identified coeval granodiorites and tonalites from the Shiquanhe area [34] and share similar characteristics with them, with some samples also exhibiting peraluminous signatures (Figure 6a). This suggests that the granodiorites exhibit transitional characteristics towards S-type granites (i.e., formed by the partial

melting of sediment rock). This conclusion further supported by their relatively uniform FeOt/MgO ratios and variable (Zr+Nb+Y+Ce) contents (Figure 6b), as well as variable SiO₂ and consistent P₂O₅ in some samples (Figure 6c). The granodiorites plot across a wide range in the C/MF vs. A/MF diagram (Figure 6d), overlapping the partial melting fields for metamorphic mudstone, metamorphic greywackes, and mafic rocks. This distribution emphasizes their transitional character towards S-type granites and indicates the input of sedimentary-derived material into the magma.

The granodiorite samples exhibit uniform FeOt+MgO+TiO₂+CaO contents and variable CaO/(FeOt+MgO+TiO₂) ratios, and they plot analogously to coeval granitic rocks from the Shiquanhe area in the CaO/(FeOt+MgO+TiO₂) vs. (FeOt+MgO+TiO₂+CaO) diagram (Figure 7a), distributing close to the mafic and amphibolite fields. This suggests the mafic rock origin of their magma. Meanwhile, the granodiorite samples plot in or close to the field of the Shiquanhe coeval granitic rocks in the Rb/Ba vs. Rb/Sr, Th/La vs. Th diagrams (Figure 7b and c). Besides, the granodiorite in this study, along with coeval granitic rocks from the Basu and Amdo areas of the BNSZ, all plot within a field with sediments contribution in the Rb/Ba vs. Rb/Sr, and Th/La vs. Th diagrams (Figure 7b and c). All these indicating a mantle-derived source with sedimentary input. Furthermore, analogous to the coeval granitic rocks from the Amdo and Shiquanhe areas [14,34], the granodiorites in this study also plot within the field of island arc volcanic rocks with sediment components in the U/Th vs. Th diagram (Figure 7d). So, we could conclude that the granodiorite magma originated from a mantle-derived mafic source with sediment input in the island arc environment.

6.3. Tectonic Setting and Its Implications

Multiple analysis of tectonic setting discrimination and trace element characteristics could define our intrusive rocks formed in a subduction-related island arc setting [16,66,67]. In the Rb-Y+Nb diagram (Figure 8a), all our samples as well as other intrusive rock samples along the SNMZ including Amdo diorites, and Basu granite are all dropped in the volcanic arc granite (VAG) field, which indicates an arc environment. In the R1-R2 diagram (Figure 8b), the samples all fall in the mantle trondhjemite field. In the Rb/30-Hf-3Ta diagram (Figure 8c), the samples also plotted in the volcanic arc granite field. Furthermore, the REE and trace element pattern of our samples are highly consistent with the standard arc granite pattern established by Poli et al. [51] and coeval arc setting granites developed in BNSZ (Figure 5) [14,49,50]. Additionally, the enrichment in large ion lithophile elements (LILEs) and depletion in high field strength elements (HFSEs) provide further evidence of the island arc setting.

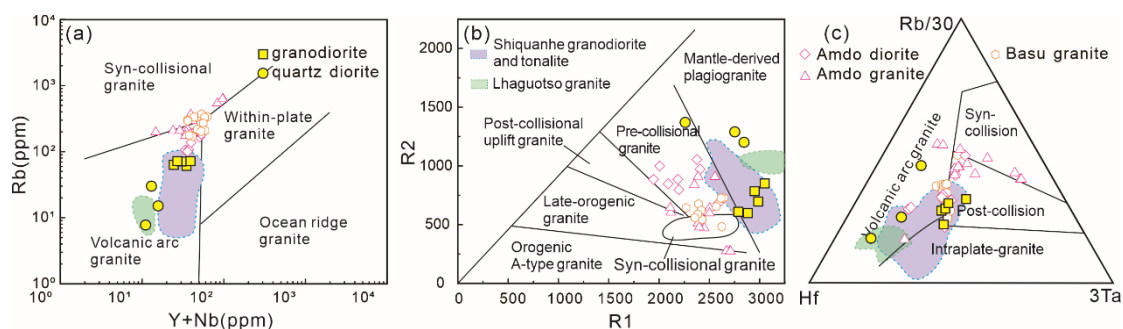


Figure 8. Geochemical data of Shiquanhe granodiorite and quartz diorite, plotted on the (a) Y+Nb vs. Rb [68], (b) R1 vs. R2 [69], (c) Rb/30-Hf-3Ta [70]. Data sources for comparison are detailed in the Figure 6.

The studied intrusive rock suits belong to the TG (tonalite-granodiorite) which are the sub-assemblage of the TTG (tonalite-trondhjemite-granodiorite) suite, so we attribute them to a TTG-like suits [59]. Additionally, their rock series are from the low-K tholeiitic to calc-alkaline series, with a prominent metaluminous attribution which are similar to the slab subduction derived trondhjemite-tonalite-dacite in modern ocean [71], especially formed in the island arc tectonic environment. Combined with the island arc setting discussed above, we suggest our Early Jurassic intrusive

samples formed in an island arc environment during the Meso-Tethys subduction stage [72–74]. Consider the newly discovery of the nearby Early Jurassic north Lameila forarc ophiolite which represent the early-stage subduction of the Bangong Meso-Tethys [23] and references therein), it is reasonable to conclude the Shiquanhe opiolitic mélange represent an island arc and back-arc assemblage rather than an independent ocean basin (Figure 9). Combine with the previous work discovered flat subduction in Gaize area [75,76], and the develop of Ga'erqiong-Galale copper-gold ore field in Shiquanhe area [77], this Early Jurassic island arc magmatism initiated a new era of the Mesozoic mineralization in SNMZ, central Tibet.

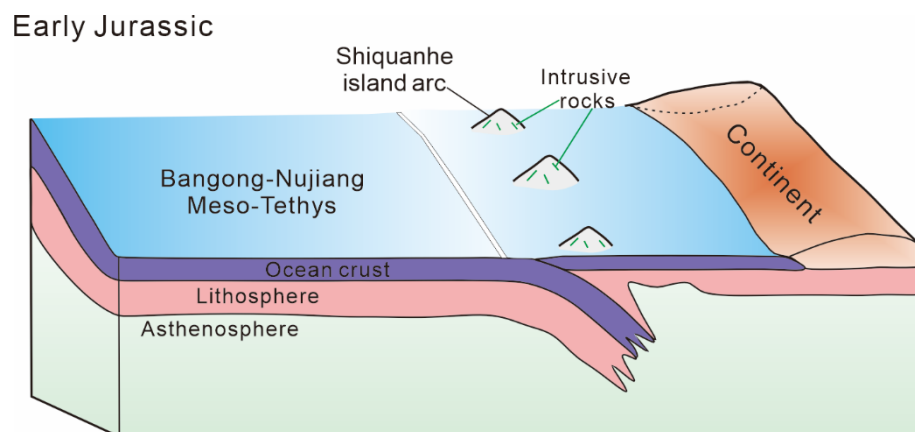


Figure 9. Cartoon showing the petrogenesis of the Shiquanhe intrusive rocks in this study. Not drawn to scale. For the specific explanation, please refer to the text.

7. Conclusions

(1) The zircon LA-ICP-MS U-Pb dating obtained the weighted mean ages of quartz diorite and granodiorite within the Shiquanhe Ophiolitic mélange are 174.7 ± 1.4 Ma and 178.9 ± 1.2 Ma respectively, indicate they are formed in Early Jurassic.

(2) The geochemistry of these Early Jurassic intermediate intrusive rocks indicates a subduction induced island arc-type TTG-like magmatism.

(3) The Shiquanhe opiolitic mélange represent an island arc and back-arc assemblage rather than an independent ocean basin.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org. Table S1. Results of zircon U-Pb dating of Shiquanhe granodiorite and quartz diorite. Table S2. Major and trace elements abundances of Shiquanhe granodiorite and quartz diorite.

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