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# Petrogenesis of the Permian Intermediate-Mafic Dikes in the Chinese Altai, Northwest China: Implication for a Postaccretion Extensional Scenario

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## ABSTRACT

The Central Asian Orogenic Belt is a long-lived accretionary orogen, and the late Paleozoic has been considered to be a critical period for the terminal amalgamation of its three tectonic collage systems. However, the exact timing of amalgamation and the geological process of such a huge accretionary orogenic belt are poorly understood. This study presents new geochronological and geochemical data for Permian intermediate-mafic dikes in the Chinese Altai, a key region between the Mongolian and the Kazakhstan collage systems. According to mineral assemblages and petrographic textures, the intermediate-mafic dikes can be categorized as gabbronorite and quartz diorite. The gabbronoritic and quartz dioritic dikes have zircon U-Pb ages of  $276.7 \pm 2.9$  and  $273.2 \pm 4.3$  Ma, respectively. The gabbronorites are characterized by low SiO<sub>2</sub> (47.1–51.3 wt%) and high MgO (5.33–8.46 wt%), together with medium Cr (71.2–95.7 ppm) and Ni (80.6–192 ppm) contents. Geochemical modeling indicates that the parental magma was possibly contaminated by 4%–12% crustal materials. Zircon  $\epsilon_{\text{Hf}}(t)$  (+13.2 to +16.7) and whole-rock  $\epsilon_{\text{Nd}}(t)$  (+4.9 to +6.1) values as well as moderate Sm/Yb ratios (1.75–1.89) imply that the parental magma might have originated from a depleted mantle source dominated by spine lherzolite. In contrast, the quartz diorites exhibit higher SiO<sub>2</sub> (57.3–58.3 wt%) and lower whole-rock  $\epsilon_{\text{Nd}}(t)$  (~+2.5) and zircon  $\epsilon_{\text{Hf}}(t)$  (+9.1 to +14.4) values, implying that they have a magma source unlike the depleted mantle of the gabbronorites. The parental magma may be derived from mafic lower crust. The quartz diorites have high Y (>39.8 ppm) and heavy rare earth element (e.g., Yb >3.64 ppm) concentrations as well as low Sr/Y (<12) ratios, consistent with geochemical fingerprints of a magma reservoir at shallow depths (<10 kb). Major element compositions of the quartz diorites are comparable to those of intermediate liquids generated by ~40% partial melting of alkali-enriched basaltic rocks at conditions of  $T = 1050^{\circ}\text{--}1100^{\circ}\text{C}$  and  $P = 8$  kbar. Such a high geothermal gradient is inferred to be a consequence of intraplating and/or underplating of hot basaltic magmas in an extensional setting, which may shed light on the ubiquitous tectonic scenario after amalgamation of tectonic collages.

**Online enhancements:** supplementary tables.

## Introduction

The Central Asian Orogenic Belt is one of the largest and longest-lived accretionary orogenic collages on earth, representing a typical region of massive

continental crust growth (Sengör et al. 1993; Sengör and Natal'in 1996; Jahn et al. 2000a, 2000b; Jahn 2004; Windley et al. 2007). Its development is believed to be a consequence of the incorporation of numerous allochthonous materials, such as island arcs, seamounts, subduction-accretion complexes, ophiolites, and microcontinents (Khain et al. 2002;

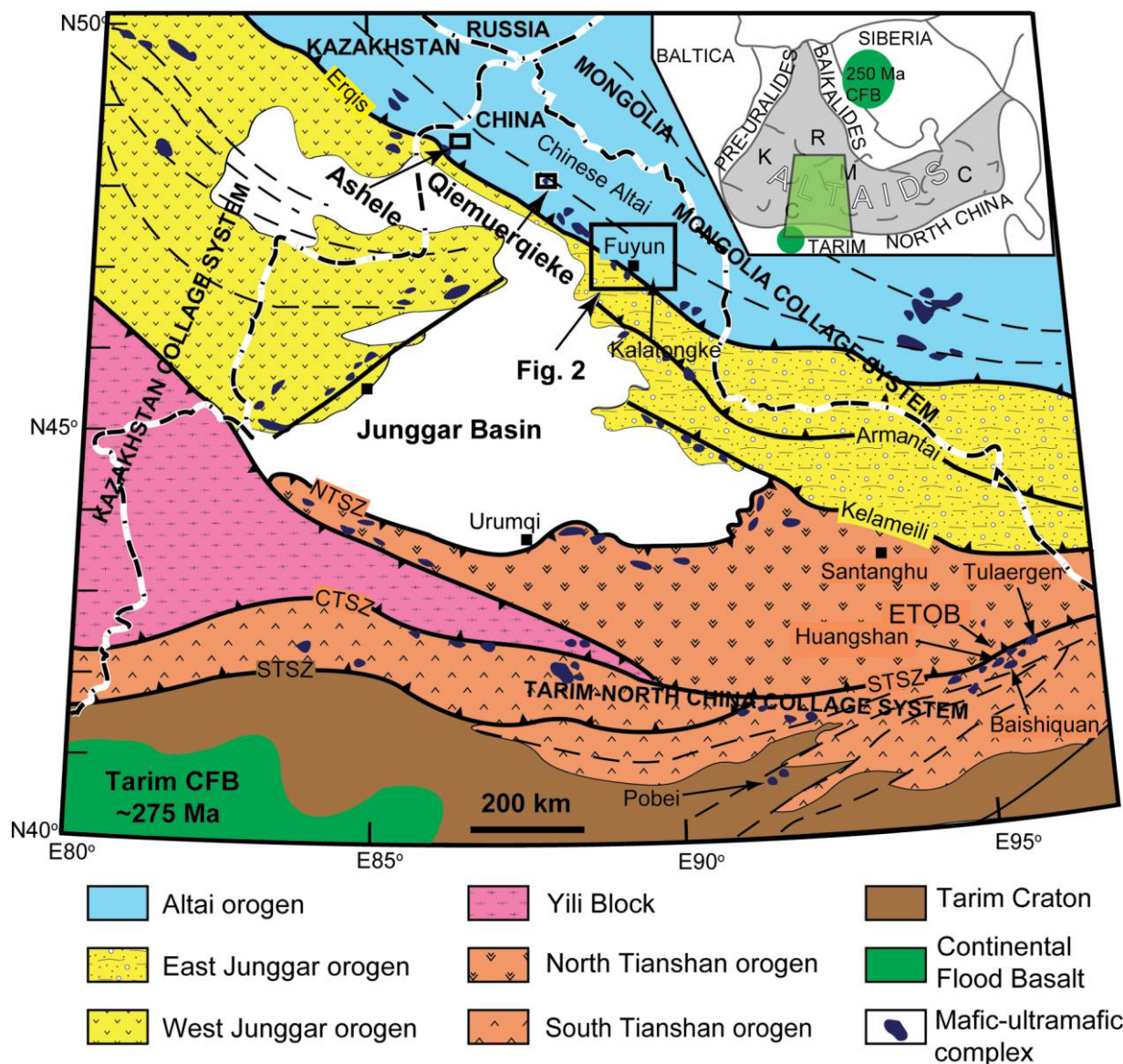
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Windley et al. 2002, 2007; Kovalenko et al. 2004; Xiao et al. 2004; Kröner et al. 2011, 2014; Wilhem et al. 2012; Xiao and Santosh 2014; Zhang et al. 2015). These diverse components merged into three independent collage systems in the early Paleozoic, namely, the Mongolian, Kazakhstan, and Tarim-North China collage systems (fig. 1; Xiao et al. 2015). However, little is known about the final tectonic process and timing of their mutual convergence in the late Paleozoic.

The Chinese Altai is situated along the southwestern margin of the Mongolian collage system and is juxtaposed with the Kazakhstan collage system to the south (fig. 1). Because of this tectonic position, the Chinese Altai is considered to be a key region to study the convergent processes and amalgamation between the Mongolian and Kazakhstan collage systems. Previous investigations documented that the Chinese Altai was a subduction-accretion complex built on the margin of Mongolian



**Figure 1.** Simplified geological map of the western Central Asian Orogenic Belt, showing the study area and adjacent regions. This is modified after Ren et al. (1999), Pirajno et al. (2008), and Wan et al. (2013). ETOB, East Tianshan ore belt; NTSZ, CTSZ, STSZ, North, Central, and South Tianshan suture zones, respectively. Box indicates the study area (Fuyun region).

collage systems in the early Paleozoic (Long et al. 2007, 2010; Sun et al. 2008; Xiao et al. 2008, 2009; Cai et al. 2011c, 2014a). However, there is much debate on its tectonic scenario in the Carboniferous to Permian, a critical period not only for its final amalgamation but also for the formation of major ore deposits in the region (Han et al. 2004; Gao and Zhou 2013). Several competing tectonic models have been recently proposed for the late Paleozoic tectonic evolution of the Chinese Altai, including oceanic subduction (Chen et al. 2006a, 2006b; Xiao et al. 2011; Wan et al. 2013; Zhang et al. 2015), postcollisional extension (Han et al. 2004; Song and Li 2009; Zhang et al. 2009; Su et al. 2011; Tong et al. 2012, 2014; Gao and Zhou 2013), slab break-off (Li et al. 2012; Gao and Zhou 2013), and mantle plume (Mao et al. 2008; Pirajno et al. 2008; Tong et al. 2014; Zhang et al. 2014). Therefore, more systematic research should be undertaken to unravel the tectonothermal events that have determined the tectonic evolution of the region. This study reports zircon U-Pb and Hf isotopic data and whole-rock geochemistry for the Permian immediate-mafic rocks from the south margin of the Chinese Altai, aiming to understand their petrogenesis and tectonic implications.

### Geological Background

The Central Asian Orogenic Belt covers an immense area that extends from the Ural Mountains on the west to the Pacific coast on the east. It is bounded by the Siberian Craton to the north and the Tarim-North China Cratons to the south (fig. 1; Zonenshain et al. 1990; Mossakovsky et al. 1993; Sengör et al. 1993; Sengör and Natal'in 1996; Jahn et al. 2000a, 2000b; Windley et al. 2002, 2007; Jahn 2004). This huge accretionary orogenic belt can be subdivided into three early Paleozoic collage systems: the Mongolian collage system, the Kazakhstan collage system, and the Tarim-North China collage system (Xiao et al. 2015). The Mongolian and Kazakhstan collage systems were bent into two separate oroclines (Xiao et al. 2004, 2008, 2010, 2013, 2015; Levashova et al. 2010, 2011), which were duplicated by slicing and striking (Sengör et al. 1993; Yakubchuk 2004) and bounded to the south by the Tarim-North China collage system (fig. 1).

The Mongolian collage system was likely a Devonian-Carboniferous ribbon-like archipelago involving numerous island arcs and subduction accretionary complexes (Badarch et al. 2002; Xiao et al. 2004, 2015; Windley et al. 2007; Wilhem et al. 2012). This collage was bent to form the Mongolian orocline, probably in Permian to Triassic time, as a result

of the collision with the Tarim-North China collage system (Lehmann et al. 2010; Bernard Edal et al. 2014; Xiao et al. 2015). The Altai Mountain Range constitutes the southwestern margin of the Mongolian orocline and extends ca. 2500 km from Russia, through Kazakhstan and China to southwestern Mongolia (Cai et al. 2011c, 2014a, 2014b). The Chinese Altai occupies the central portion of the Altai Mountain Range and is subdivided into the North Altai, Central Altai, Qionghuer Domain, and South Altai (BGMRX 1993; Windley et al. 2002; Long et al. 2007, 2010; Cai et al. 2010, 2011c, 2012a). The North Altai is mainly composed of late Devonian-early Carboniferous neritic clastic sedimentary rocks, arc volcanic rocks, and greenschists. The Central Altai is underlain by thick turbiditic and pyroclastic sedimentary sequences, most of which were deformed and folded with steep axial planes. Voluminous granitic rocks and several mafic-ultramafic stocks intruded these sedimentary sequences. The Qionghuer Domain contains late Silurian sedimentary rocks (Kulumutu Group), Early Devonian arc pyroclastic rocks (Kangbutiebao Formation), and middle Devonian turbidites (Altai Formation). Rocks of this domain were metamorphosed to greenschist or upper amphibolite facies and locally to granulite facies. The South Altai consists of Devonian fossil-bearing sedimentary rocks and late Carboniferous volcanoclastic rocks that underwent greenschist to amphibolite facies metamorphism (He et al. 1990; Windley et al. 2002; Cai et al. 2011a, 2011b, 2011c, 2012a).

To the south, the Chinese Altai is separated by the Erqis Fault—a large-scale (1000 km) sinistral strike-slip fault—from the Junggar composite terrane, which consists of East Junggar, West Junggar, and Junggar basins (fig. 1). The East Junggar includes NW-striking Dulate and Yemaquan island arcs, which are separated by the highly deformed and dismembered Armantai ophiolite belt (Xiao et al. 2004, 2009; Long et al. 2012; Cai et al. 2014b). The Dulate arc is situated along the north side of the Armantai ophiolite and includes Devonian-Carboniferous volcanic rocks, such as picrite, boninite, high-Mg andesite, and Nb-rich basalt (Zhang et al. 2003, 2004). The Yemaquan arc is located to the south of the Armantai ophiolite and is dominated by Ordovician-Carboniferous clastic rocks and carbonates, with subordinate volcanoclastic rocks (Xiao et al. 2009, 2011; Long et al. 2012). A plagiogranite from the Armantai ophiolitic mélange yielded a SHRIMP zircon age of  $503 \pm 7$  Ma (Xiao et al. 2009). The Junggar Basin is a large petroliferous basin covered by several kilometers of Mesozoic sedimentary rocks, and its basement nature remains a subject of debate (Carroll et al.

1990; Han et al. 1999; Xu et al. 2013, 2015). The West Junggar constitutes a portion of the Kazakhstan collage system that formed by multiple accretions of seamounts, intra-ocean arcs, ophiolite fragments, and subduction complexes during the Middle Cambrian to Carboniferous (Carroll et al. 1995; Chen and Jahn 2004; Han et al. 2004; Jahn 2004; Xiao et al. 2004, 2009). The Kazakhstan collage system includes the Chingiz arc, the Kokchetav microcontinent, and the North Tianshan–Yili arc and is interpreted to occur as a long composite arc in the early Paleozoic. This composite arc was converted to the Kazakhstan orocline through bending in the late Paleozoic (Xiao et al. 2015). The northern limb of the Kazakhstan orocline is represented by the Chingiz arc that extends almost to the Erqis Fault in the north, and the southern limb is denoted by the Yili arc. The Kazakhstan orocline was proposed to have an association with ridge subduction in the late Carboniferous in the West Junggar (Geng et al. 2009; Xiao et al. 2010, 2015; Yin et al. 2010; Choulet et al. 2012; Ma et al. 2012).

### Regional Geology and Sample Descriptions

The south Chinese Altai is characterized by widespread occurrences of magmatic rocks and complex fault systems. The study area is bracketed by the Fuyun fault in the east, the Kurti fault in the southwest, and the Abagong fault in the north (fig. 2). The Fuyun fault has typical characteristics of ductile shear deformation, indicated by S-C fabrics, asymmetric folding, and augen structure. The ductile shear zone is characterized by steeply NE-dipping penetrative mylonitic foliation and gently plunging subhorizontal stretching lineation. The Kurti and Abagong faults are considered to be two separate branches of an imbricated thrust fault system (fig. 2), and they occur broadly parallel to the orientation of the Irtysh thrust in this area. The majority of magmatic intrusions were emplaced in the Devonian (Wang et al. 2006; Yuan et al. 2007; Cai et al. 2010, 2011a, 2011b, 2011c); however, intermediate and mafic magmatic rocks, the focus of this study, were mainly emplaced in the Permian. The Permian magmatic rocks are distributed along two fault systems (fig. 2). The northern belt is along the NNW-SSE-trending Fuyun fault zone, and the rocks of this belt intruded the Ordovician Habahe Group. The southern belt is along the NW-SE-trending Kurti fault zone, and the rocks of this belt intruded the Silurian and Devonian strata. Field investigations show that the studied intermediate and mafic dikes vertically intruded the granitoid rocks and paragneisses, and their width varies from several meters to tens of meters (fig. 2). The dikes are fresh, with much weaker deformation

than the surrounding granitoid rocks and paragneisses. Based on the mineral assemblages and petrographic textures, the intermediate-mafic dikes can be categorized as gabbro-norite and quartz diorite, respectively.

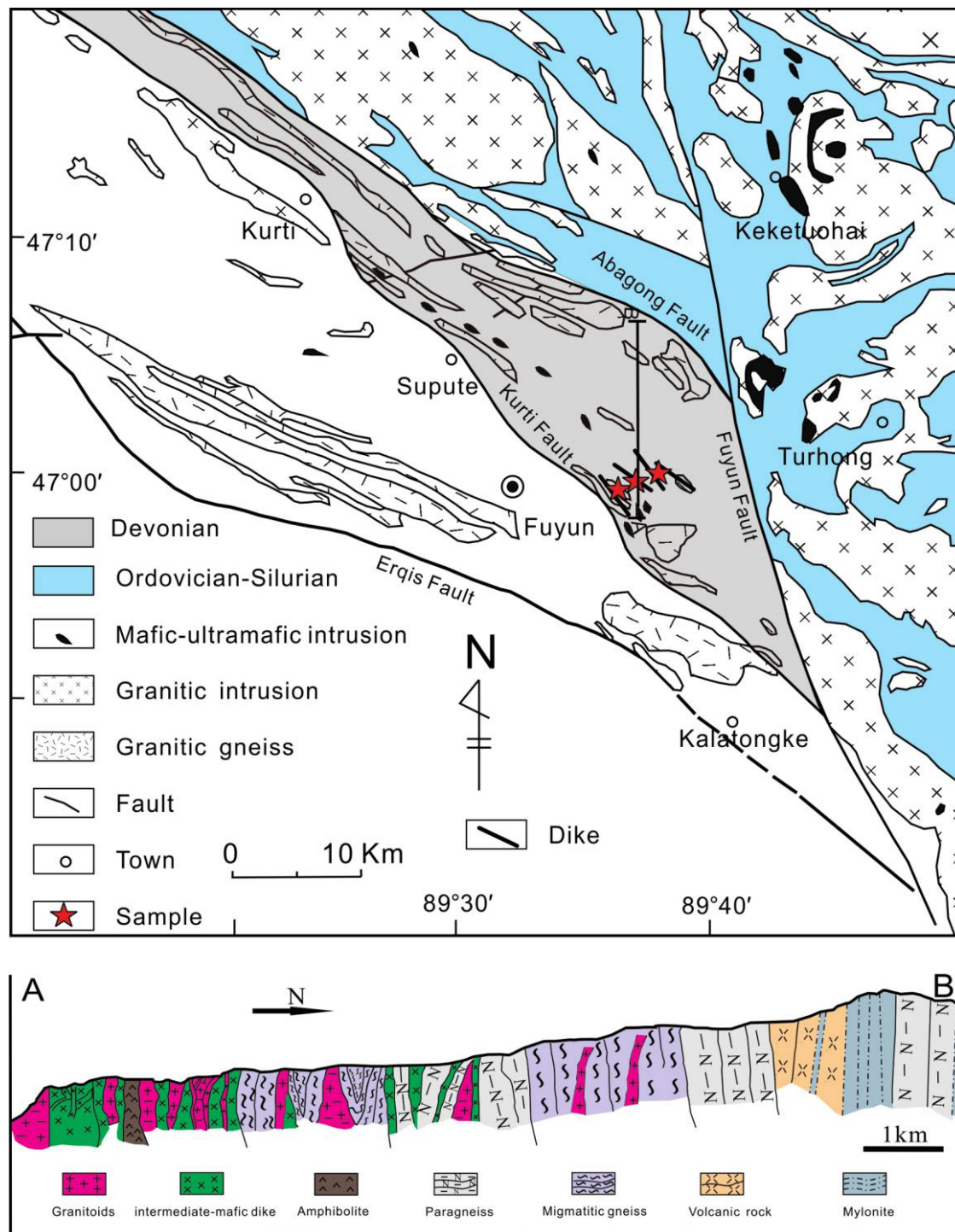
The gabbro-norite consists of plagioclase (40–50 vol%), orthopyroxene (20–30 vol%), and clinopyroxene (10–20 vol%), with minor contents of magnetite, Cr-spinel, and ilmenite (fig. 3b). Plagioclase grains are euhedral to subhedral and 1–5 mm in length, while clinopyroxene, orthopyroxene, and other minerals are subhedral to anhedral. Clinopyroxene and orthopyroxene commonly show variable chloritization, and plagioclase shows the features of sericitization and kaolinization. Quartz diorite consists of quartz (10–20 vol%), plagioclase (50–60 vol%), and hornblende (20–30 vol%), with minor apatite, magnetite, and zircon. The quartz dioritic rocks have a granular texture characterized by interlocking hornblende and plagioclase (fig. 3d). Plagioclase grains are subhedral to anhedral and are 0.5–2 mm in length. Anhedral to subhedral hornblende has irregular shapes and is embedded in the interstices among plagioclase grains. Anhedral quartz grains have sizes ranging from 0.2 to 1.0 mm in length.

### Analytical Methods

#### *Zircon Separation and Cathodoluminescence Imaging.*

After sample crushing, zircons were separated by standard heavy liquid and magnetic techniques. Crystal grains from the >25  $\mu\text{m}$  nonmagnetic fractions were handpicked and mounted on adhesive tape, enclosed in epoxy resin, and polished to about half of their thickness. Cathodoluminescence images were taken, using a JXA-8100 electron probe micro-analyzer with a Mono CL3 cathodoluminescence system for high-resolution imaging and spectroscopy, at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, to investigate internal structures and to choose potential target sites for U-Pb and Hf analyses.

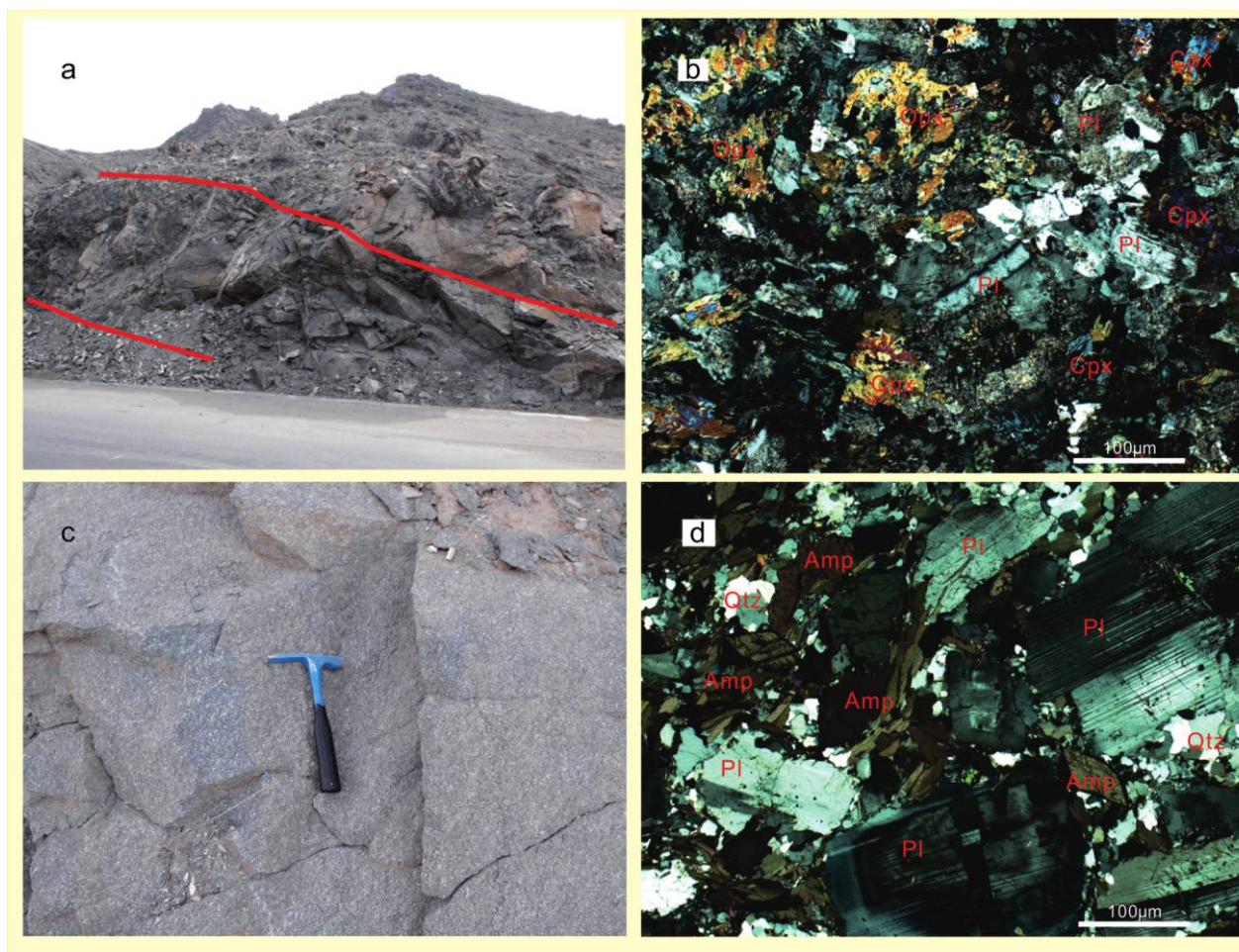
***Zircon U-Pb Dating.*** Zircon U-Pb isotopic analyses were performed at the Department of Earth Sciences, University of Hong Kong. A 193-nm excimer laser ablation system (Resolution M-50) was used in connection with a Nu Plasma multicollector inductively coupled plasma mass spectrometer (MC-ICP-MS). Helium gas, which carries the laser-ablated sample aerosol from sample cell, was mixed with argon carrier gas and nitrogen as additional diatomic gas to enhance sensitivity and finally flows into the MC-ICP-MS torch for analysis. The detailed analytical procedure is described by Xia et al. (2011). The majority of the analyses were conducted with a beam



**Figure 2.** Distributions of dikes and mafic-ultramafic intrusions in the Fuyun area (A) and cross section of the study area (B; after Cai et al. 2012a).

diameter of 30  $\mu\text{m}$ , repetition rate of 5 Hz, and energy of  $\sim 5 \text{ J}/\text{cm}^2$  per pulse. Zircons 91500 and GJ-1 were used as the external standards for calibration. The mass fractionation correction and isotopic results were calculated by ICPMSDataCal (ver. 7.0; Liu et al.

2008). A common Pb correction was applied to all measured ratios using the interference and background-corrected  $^{204}\text{Pb}$  signal intensity, following the approach of Andersen (2002). Age calculation and concordia plots were processed using ISOPLOT 3.0



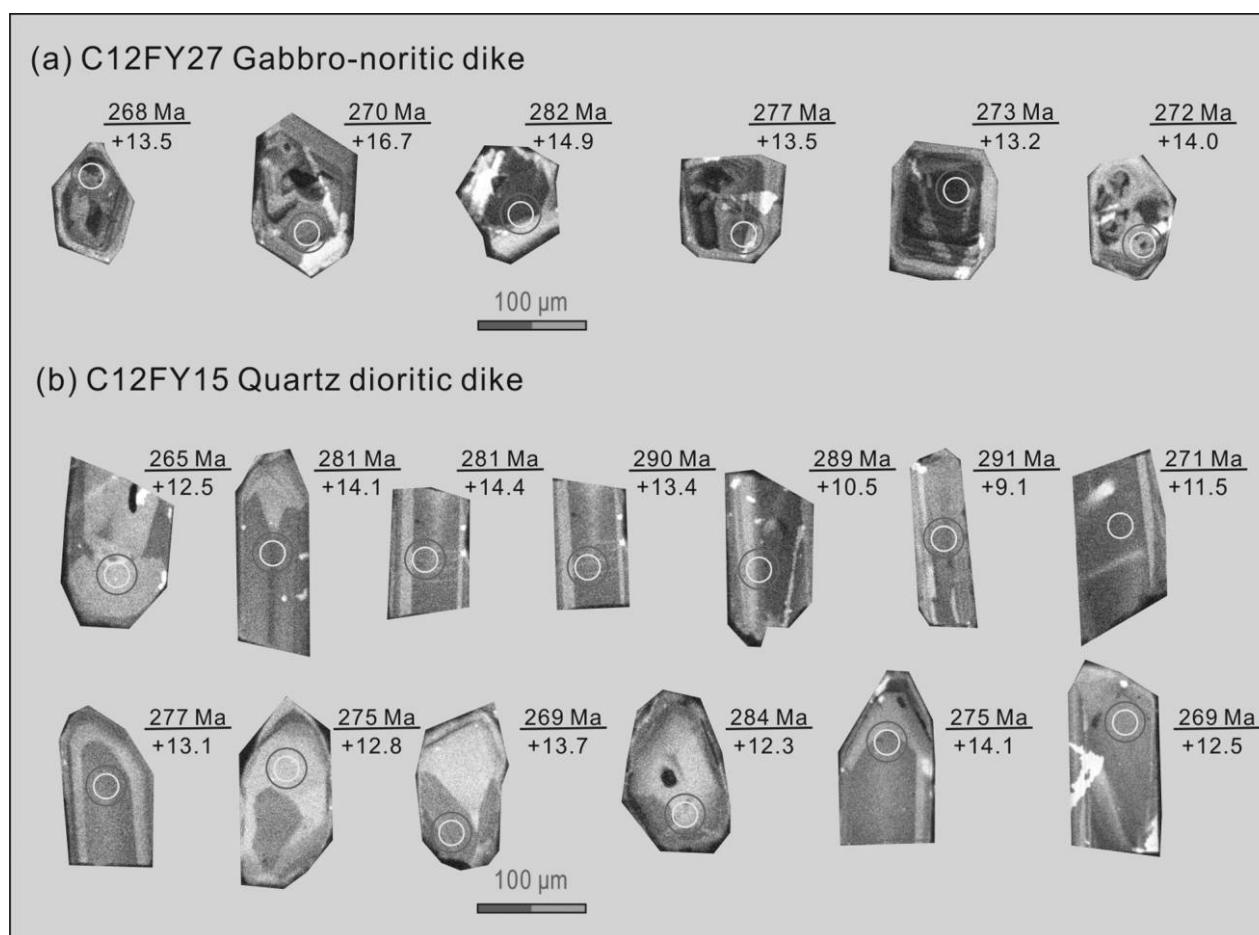
**Figure 3.** Field photo of the gabbro noritic dikes (a), microscope photo of the thin section of the gabbro noritic rock (b), field photo of the quartz dioritic dikes (c), and microscope photo of the thin section of the quartz diorites (d) in the Fuyun region. Pl, plagioclase; Qtz, quartz; Cpx, clinopyroxene; Opx, orthopyroxene; Amp, amphibole.

(Ludwig 2003). Individual analyses are presented with  $1\sigma$  error in table S1 (tables S1–S5 available online) and in concordia diagrams (fig. 5). Uncertainties of mean age calculations are quoted at the 95% level.  $^{206}\text{Pb}/^{238}\text{U}$  ages are used for grains  $<1.0$  Ga, and  $^{207}\text{Pb}/^{206}\text{Pb}$  ages are used for grains  $>1.0$  Ga, according to Black et al. (2003). The U–Pb isotopic data are shown in table S1.

**Zircon Lu–Hf Isotopic Analyses.** Zircon Hf isotope analyses were performed using the laser ablation system Resolution M-50, attached to a Nu Plasma high-resolution MC-ICP-MS, at the Department of Earth Sciences, the University of Hong Kong. A spot size of  $40\ \mu\text{m}$  was used for most analyses and the ablation spot for Hf isotope analysis was sited at the same cathodoluminescence domain for the U–Pb dating. The standard zircon 91500 was used as a reference standard, with a weighted mean  $^{176}\text{Hf}/^{177}\text{Hf}$  ratio of  $0.282298 \pm 6$  ( $2\sigma$ ,  $n = 50$ ), similar to the recommended  $^{176}\text{Hf}/^{177}\text{Hf}$  ratio of  $0.282306 \pm 10$

(Woodhead et al. 2004). Detailed instrumental settings and analytical procedures were as described by Xia et al. (2011). All Hf isotope data were calculated using the decay constant of  $1.865 \times 10^{-11}\ \text{yr}^{-1}$  (Schärer et al. 2001). The chondritic values of  $^{176}\text{Hf}/^{177}\text{Hf} = 0.282772$  and  $^{176}\text{Lu}/^{177}\text{Hf} = 0.0332$  (Blichert-Toft and Albarede 1997) were used for the calculation of  $\epsilon_{\text{Hf}}(t)$  values. The depleted mantle Hf model ages ( $T_{\text{DM}}$ ) were calculated using the measured  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios of zircon, assuming that the depleted mantle reservoir has a linear growth from  $^{176}\text{Hf}/^{177}\text{Hf} = 0.279718$  at 4.55 Ga to 0.283250 at present, with a  $^{176}\text{Lu}/^{177}\text{Hf}$  value of 0.0384 (Griffin et al. 2000). The Lu–Hf isotopic results are presented in table S2.

**Major and Trace Element Analyses.** Major oxides were determined by wavelength-dispersive X-ray fluorescence spectrometry on fused glass beads, using a Rigaku RIX 2000 X-ray fluorescence spectrometer at the Guangzhou Institute of Geochemistry, Chi-



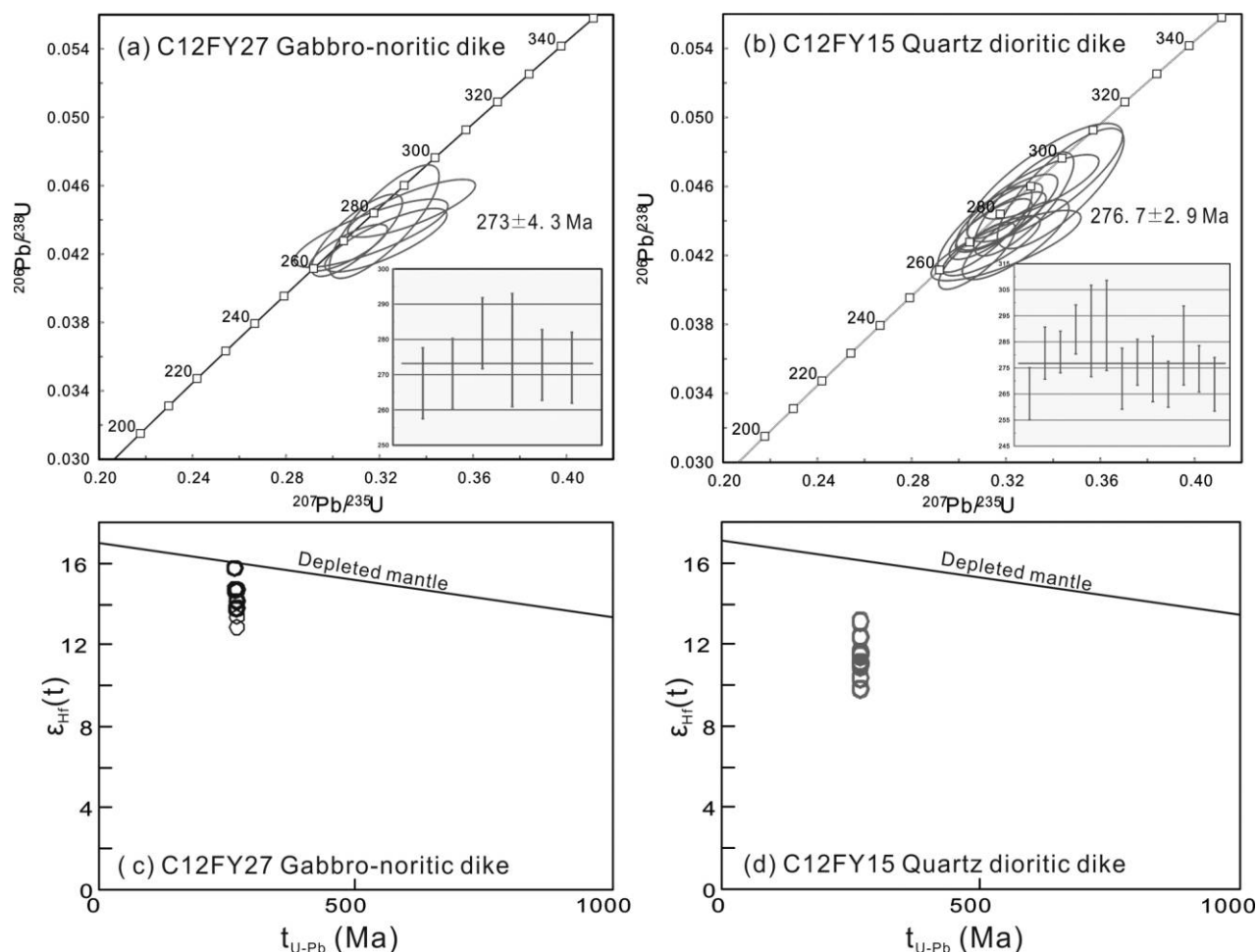
**Figure 4.** Cathodoluminescence images of the analyzed zircon grains from the gabbro-noritic and quartz dioritic dikes. Circles denote the analyzing locations, and numbers refer to U-Pb ages and  $\epsilon_{\text{Hf}}(t)$  values. A color version of this figure is available online.

nese Academy of Sciences. Calibration lines used in quantification were produced by bivariate regression of data from 36 reference materials encompassing a wide range of silicate compositions (Li et al. 2006), and analytical uncertainties are 1%–5%. The trace elements—including rare earth elements (REEs), high field strength elements (HFSEs), and large ion lithophile elements (LILEs)—were determined with a Perkin-Elmer Sciex ELAN 6000 ICP-MS, using nebulized sample solutions also at the Guangzhou Institute of Geochemistry. Analytical procedures are similar to those described by Liu et al. (1996) and Li (1997). Approximately 50-mg sample powders were dissolved in high-pressure Teflon bombs, using an HF + HNO<sub>3</sub> mixture. An internal standard solution containing the single element Rh was used to monitor signal drift during counting. A set of international and Chinese national rock standards—including BHVO-2, MRG-1, SY-4, G-2, and GSP-2 and GSR-1, GSR-2, GSR-3, and GSD-12—were used for calibrating ele-

ment concentrations of unknowns. Analytical errors are generally <15%. The major and trace element results are presented in table S3.

**Sr-Nd Isotope Analyses.** Samples for Sr and Nd isotopic analysis were decomposed in a mixture of HF-HClO<sub>4</sub>, and Sr and Nd were separated using a two-step ion exchange procedure. The <sup>87</sup>Sr/<sup>86</sup>Sr and <sup>143</sup>Nd/<sup>144</sup>Nd ratios were measured on a Micromass IsoProbe MC-ICP-MS at the Guangzhou Institute of Geochemistry, following the procedures described by Wei et al. (2002) and Liang et al. (2003). <sup>83</sup>Kr, <sup>84</sup>Sr, <sup>85</sup>Rb, <sup>86</sup>Sr, <sup>87</sup>(Rb + Sr), and <sup>88</sup>Sr were simultaneously measured to monitor the interference of <sup>84</sup>Kr, <sup>86</sup>Kr, and <sup>87</sup>Rb on Sr isotopes. Kr interference comes predominantly from Ar gas and is generally at a very low level (0.015%) and can be effectively eliminated after blank correction. Interference of <sup>87</sup>Rb can be estimated using <sup>85</sup>Rb/<sup>87</sup>Rb = 2.59265 and a mass fractionation factor calculated on the basis of measured <sup>86</sup>Sr/<sup>88</sup>Sr ratios and <sup>86</sup>Sr/<sup>88</sup>Sr = 0.1194. NBS987





**Figure 5.** Laser ablation inductively coupled plasma mass spectrometry U-Pb zircon concordia diagrams and Hf isotopes for the gabbro-noritic dikes and the quartz dioritic dikes. A color version of this figure is available online.

was used as the standard to monitor the instrumental performance for Sr isotope analyses, and multiple analyses of NBS987 yielded an average  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of  $0.710247 \pm 17$  ( $2\sigma$ ). Repeated analyses for the Shin Estu JNdi-1 standard during the course of this study yielded an average  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of  $0.512120 \pm 8$  ( $2\sigma$ ). Accordingly, the  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios reported in this study were adjusted relative to the Shin Estu JNdi-1 reference value of 0.512115 (Tanaka et al. 2000), corresponding to the La Jolla standard value of 0.511860. The  $^{87}\text{Rb}/^{86}\text{Sr}$  and  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios were calculated from the Rb-Sr and Sm-Nd concentrations determined by trace element analysis. The Sr and Nd isotopic compositions are listed in tables S4 and S5.

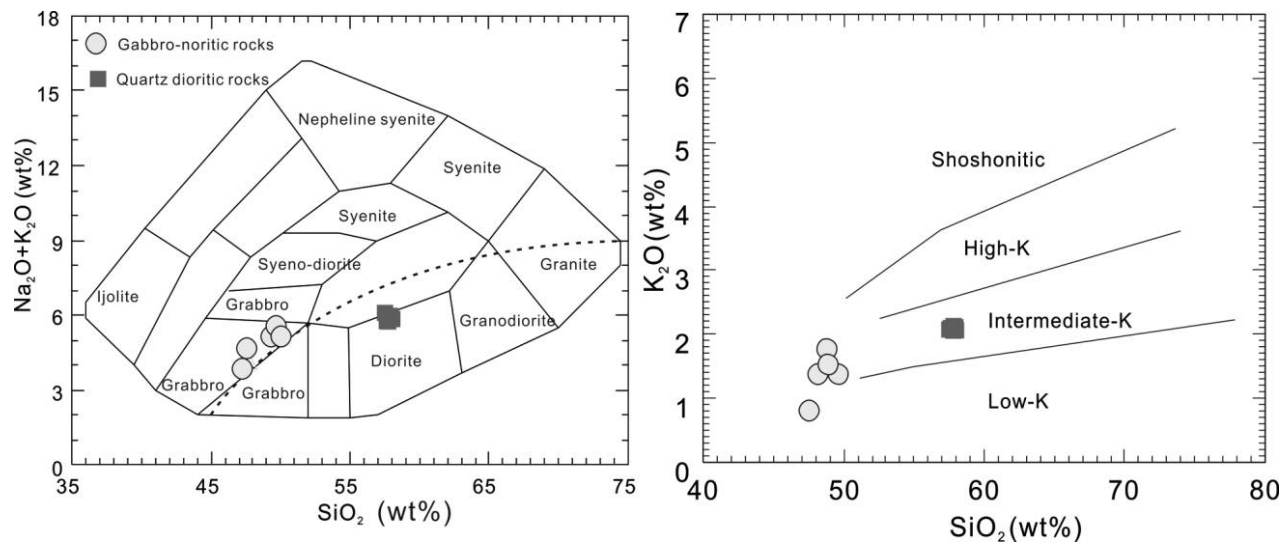
### Analytical Results

**Zircon U-Pb Age and Hf Isotopes.** Zircon grains from the gabbro-norite are generally colorless and transparent and are characterized by euhedral prismatic

shapes, concentric oscillatory zoning (fig. 4a), and high Th/U ratios (0.41–1.16), indicating an igneous origin. Six analyses define a coherent age population with a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $273.2 \pm 4.3$  Ma (fig. 5a), which is considered to record timing of emplacement for the gabbro-norite. The calculated  $\epsilon_{\text{Hf}}(t)$  values range from +13.2 to +16.7 (fig. 5c), and  $T_{\text{DM}}$  model ages are 318–387 Ma.

Zircon grains separated from the quartz diorite are prismatic and euhedral (fig. 4b), with high Th/U ratios (0.62–1.50), suggesting that they are also igneous in origin. Thirteen analyses yielded a coherent age population with a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $276.7 \pm 2.9$  Ma (fig. 5b), which is taken as the intrusive age of the quartz diorite. The  $\epsilon_{\text{Hf}}(t)$  values calculated at 277 Ma are between +9.1 and +14.4 (fig. 5d), with  $T_{\text{DM}}$  model ages of 342–546 Ma.

**Geochemical Characteristics.** The gabbro-norites are characterized by high  $\text{TiO}_2$  (1.92–2.48 wt %) and show a narrow range of  $\text{SiO}_2$  (47.1–51.3 wt %; figs. 6a, 7).



**Figure 6.** Na<sub>2</sub>O + K<sub>2</sub>O versus SiO<sub>2</sub> diagram (left; Cox et al. 1980) and K<sub>2</sub>O versus SiO<sub>2</sub> plot (right) for the gabbro-noritic and quartz dioritic dikes in the Fuyun region, Chinese Altai. A color version of this figure is available online.

Their MgO contents vary from 5.33 to 8.46 wt% (Mg# = 52.3–62.8). They are alkali rich (K<sub>2</sub>O + Na<sub>2</sub>O = 3.55–5.12 wt%; K<sub>2</sub>O ≥ 0.74 wt%) and mainly plot in the moderate-high K fields (fig. 6b). In Harker diagrams (fig. 7), TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub><sup>T</sup>, and MgO decrease with increasing SiO<sub>2</sub>, while K<sub>2</sub>O and Na<sub>2</sub>O exhibit positive correlations with SiO<sub>2</sub> (fig. 7). The REE patterns show coherent enrichments of LREE ((La/Yb)<sub>N</sub> = 3.77–4.52) and flat heavy rare earth element (HREE) patterns ((Gd/Yb)<sub>N</sub> = 1.61–1.76), with weak negative Eu anomalies (Eu\*/Eu = 0.82–0.94; fig. 8a). In the primitive mantle-normalized multi-element diagram, all gabbro-norite samples show similar trends of significant enrichments in LILEs relative to HFSEs (fig. 8b).

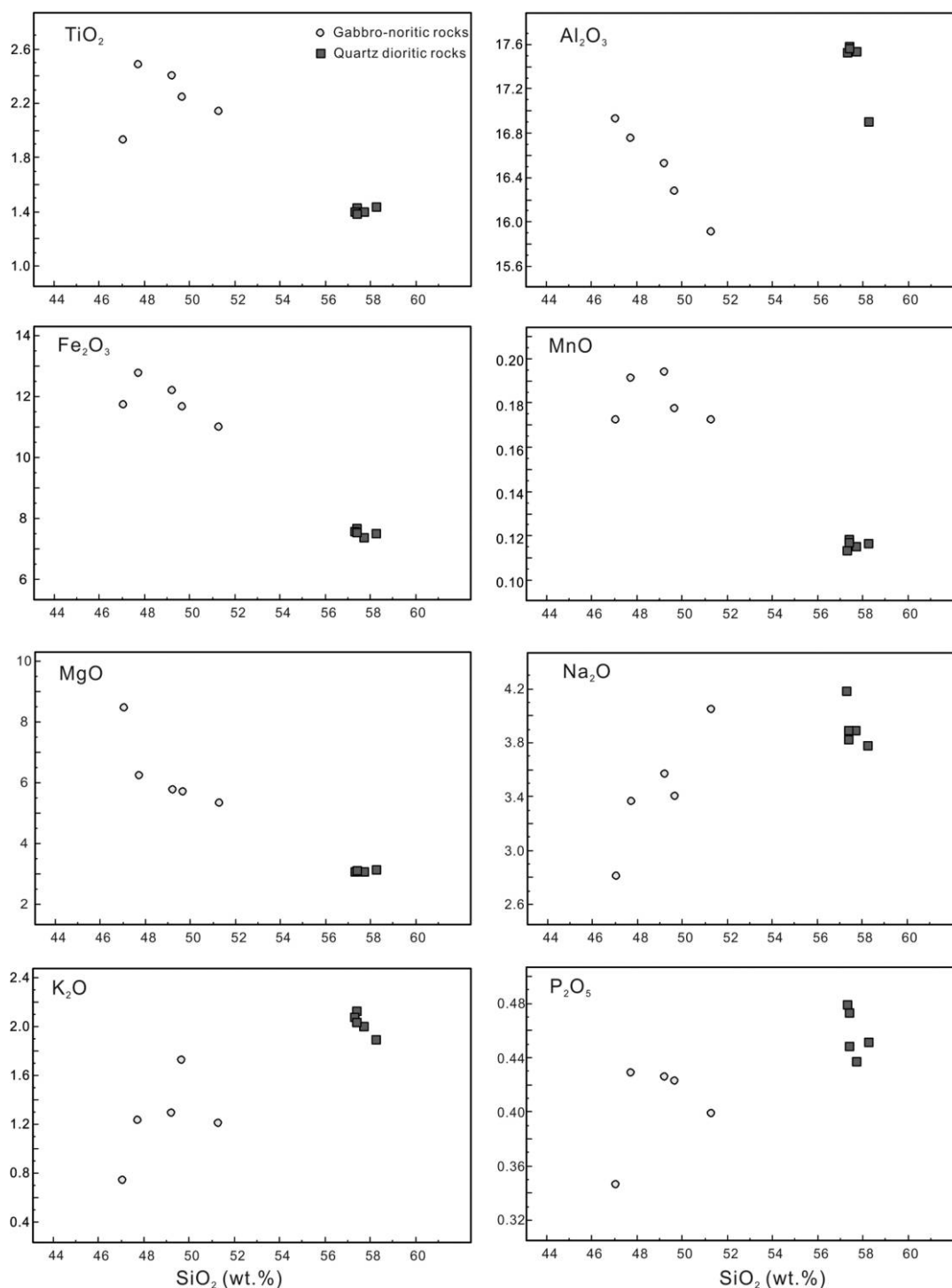
The quartz diorites have relatively higher SiO<sub>2</sub> contents (57.3–58.3 wt%) and lower TiO<sub>2</sub> (1.38–1.43 wt%) than those of the gabbro-norites (figs. 6a, 7). They display lower MgO contents (3.03–3.13 wt%) and Mg# of 48.5–49.3 relative to the gabbro-norites. All samples plot in the medium-high K fields (fig. 6b), with high K<sub>2</sub>O contents (≥1.89 wt%). In Harker diagrams, no linear variation is shown between major oxides and SiO<sub>2</sub> (fig. 7). The quartz diorites have lower Cr and Ni but higher total REE contents than those of the gabbro-norites (fig. 8c) and show moderately negative Eu anomalies (Eu\*/Eu = 0.63–0.69), slightly enriched LREE ((La/Nd)<sub>N</sub> = 9.42–10.62), and relatively flat HREE ((Gd/Yb)<sub>N</sub> = 1.87–2.04). Similarly, in the primitive mantle-normalized trace element diagram, the quartz diorites have coherent patterns, with enrichment in LILEs (e.g., U and Pb), negative HFSEs (e.g., Nb, Ta, Zr, and Hf) and Sr, and Eu anomalies (fig. 8d).

**Sr-Nd Isotopic Compositions.** The gabbro-norite samples have  $\epsilon_{\text{Nd}}(t)$  values of +4.9 to +6.1 and initial ratios of  $^{87}\text{Sr}/^{86}\text{Sr}_{(i)} = 0.7036\text{--}0.7038$  that resemble those of the Permian hornblende gabbros ( $\epsilon_{\text{Nd}}(t) = +4.8$  to +6.0,  $^{87}\text{Sr}/^{86}\text{Sr}_{(i)} = 0.7034\text{--}0.7035$ ) and the Triassic continental basalts ( $\epsilon_{\text{Nd}}(t) = +4.3$  to +5.2,  $^{87}\text{Sr}/^{86}\text{Sr}_{(i)} = 0.7047\text{--}0.7052$ ; Yuan et al. 2011; Wan et al. 2013) in the region but are lower than those of the Permian mafic intrusions in the Kalatongke area ( $\epsilon_{\text{Nd}}(t) = +6.3$  to +8.2,  $^{87}\text{Sr}/^{86}\text{Sr}_{(i)} = 0.7038\text{--}0.7050$ ; Zhang et al. 2009). The quartz diorites exhibit lower  $\epsilon_{\text{Nd}}(t)$  values ( $\sim +2.5$ ) and higher initial ratios of  $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$  (0.7048) than those of the gabbro-norite samples (fig. 9) but are close to those of the Devonian Keke-tuohai mafic-ultramafic complex ( $\epsilon_{\text{Nd}}(t) = 0$  to +2.7,  $^{87}\text{Sr}/^{86}\text{Sr}_{(i)} = 0.7046\text{--}0.7062$ ; Cai et al. 2012b).

## Discussion

### *Petrogenesis and Magma Source of the Gabbro-norites.*

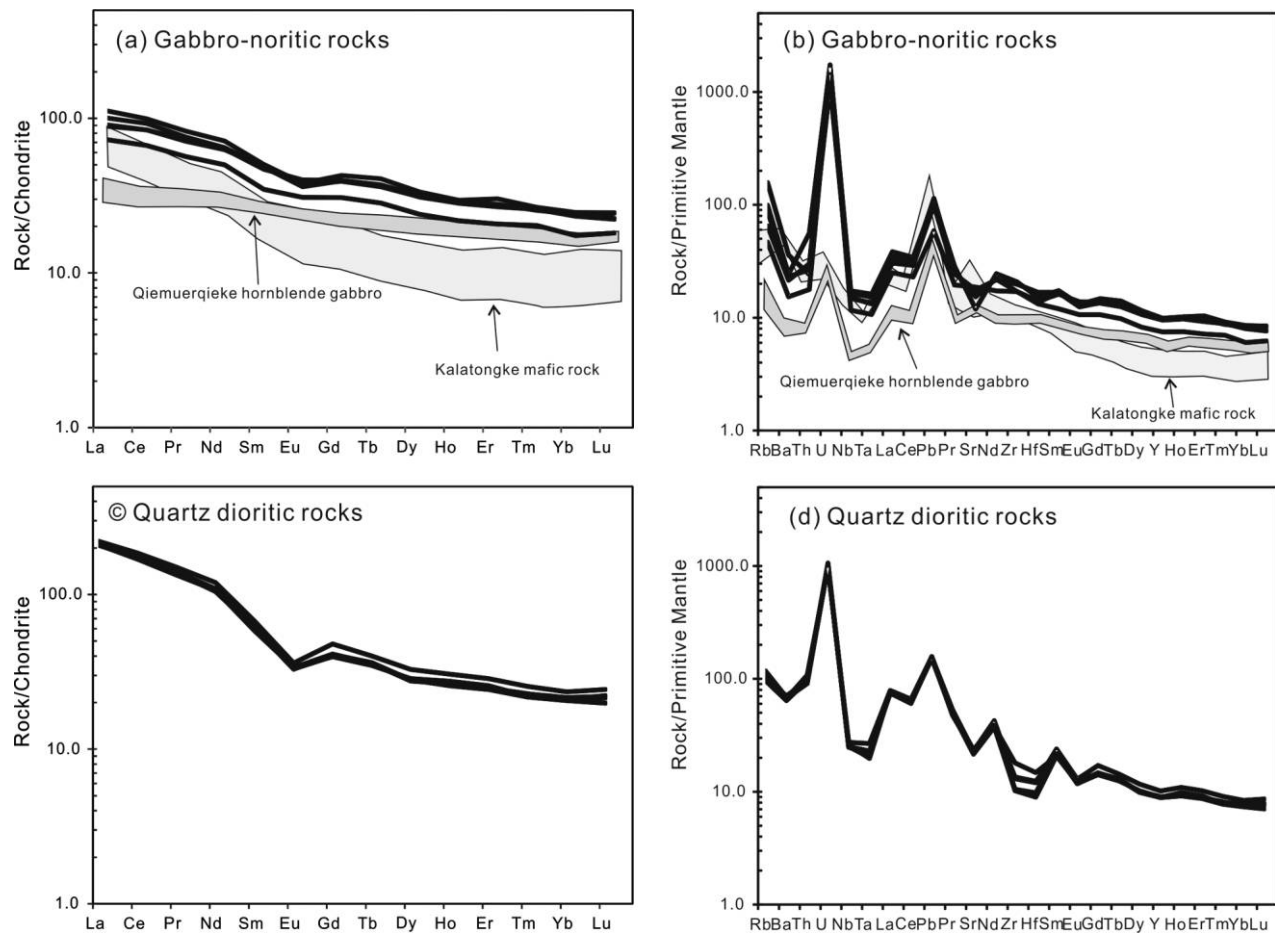
Since pyroxenes are partly replaced by chlorite and plagioclases show features of sericitization, it is necessary to evaluate the element mobility of the gabbro-norites before discussing their petrogenesis and source nature. We note that the gabbro-noritic rocks have a relatively low loss on ignition index (LOI = 0.80–1.74 wt%), and their trace elements display coherent patterns in the primitive mantle-normalized spider diagram (fig. 8), which are considered as evidence of only a weak influence on chemical compositions by the mineral alteration. Accordingly, the geochemical data should, to a great extent, faithfully record the original compositions. The gabbro-norites have low SiO<sub>2</sub> (47.1–51.3 wt%) and high MgO (5.33–



**Figure 7.** Variation diagrams for major oxides versus  $\text{SiO}_2$  for the gabbro-noritic and quartz dioritic dikes. Symbols as in figure 6. A color version of this figure is available online.

8.46 wt%) contents as well as high zircon  $\epsilon_{\text{Hf}}(t)$  (+13.2 to +16.7) and whole-rock  $\epsilon_{\text{Nd}}(t)$  (+4.9 to +6.1) values, suggesting parental magma derivations from a depleted mantle source. Compared with those of the primitive basalts ( $\text{Mg\#} = 63\text{--}73$ ,  $\text{Ni} = 84.6\text{--}442$  ppm,  $\text{Cr} =$

266–975 ppm; Green 1975; Frey et al. 1978; Hess 1992; Kelemen et al. 2003), variations of  $\text{Mg\#}$  (52.3–62.8) and lower Ni (80.6–192 ppm) and Cr (71.2–95.7 ppm) contents may be due to fractional crystallization of ferromagnesian minerals (e.g., olivine, pyroxene, and/

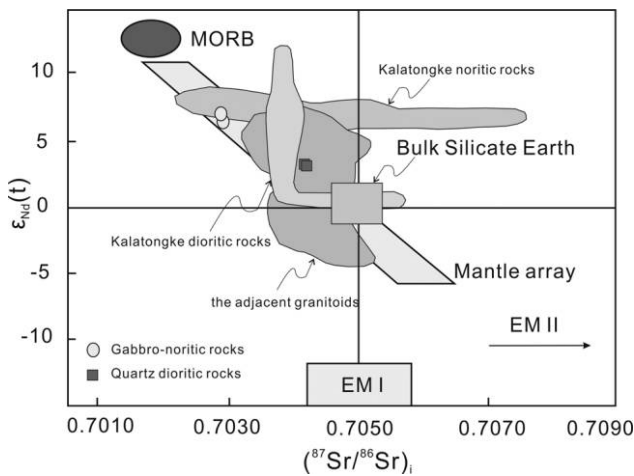


**Figure 8.** Chondrite-normalized rare earth element patterns and primitive mantle-normalized trace element spider diagram for the gabbro-noritic and quartz dioritic dikes. Normalizing values are from Sun and McDonough (1989). Symbols as in figure 6. A color version of this figure is available online.

or Cr spinel) and/or crustal contamination. However, the limited variation of  $\text{SiO}_2$  (47.1–51.3 wt%) denotes a weak influence of fractional crystallization during magma evolution.

Crustal contamination may occur in the mantle source, along the route of magma ascent, and/or during final emplacement. Because the bulk crust has higher  $(\text{Th}/\text{Yb})_N$  and lower  $(\text{Ta}/\text{Th})_N$  than those of mantle-derived magma,  $(\text{Th}/\text{Yb})_N$  and  $(\text{Ta}/\text{Th})_N$  are generally applied as valid parameters to estimate the degree of crustal contamination (fig. 10a). Compared with normal mid-ocean ridge basalt (N-MORB) and enriched MORB (E-MORB), the gabbro-norites are characterized by strikingly higher  $(\text{Th}/\text{Yb})_N$  and lower  $(\text{Ta}/\text{Th})_N$  ratios. If the average composition of the Devonian low-grade metamorphic sediments is taken as the potential crustal contaminant, our samples do not well match the modeling curves defined by either an N-MORB or E-MORB single mantle source. Alternatively, if a

mixed mantle source is chosen for the magma source, the result suggests that the extent of crustal contamination of the gabbro-norite rocks may be between 4% and 12% (fig. 10a). Nevertheless, such a low degree of crustal contamination is consistent with the strikingly positive zircon  $\varepsilon_{\text{Hf}}(t)$  (+13.2 to +16.7) and whole-rock  $\varepsilon_{\text{Nd}}(t)$  (+4.9 to +6.1) values and the coherent REE and HFSE contents of these rocks. Because Yb ( $D_{\text{spinel/melt}} = 0.0045$ ) and Sm ( $D_{\text{spinel/melt}} = 0.0006$ ) have similar partition coefficients, partial melting of spinel lherzolite generally gives constant Sm/Yb ratios (Aldanmaz et al. 2000; Green 2006). In contrast, garnet has significant uptakes of Yb ( $D_{\text{garnet/melt}} = 6.6$ ) over Sm ( $D_{\text{garnet/melt}} = 0.25$ ); thus, partial melting of garnet peridotites results in elevated Sm/Yb ratios (Johnson 1994). The gabbro-norites have Sm/Yb ratios (1.75–1.89) and Sm contents (5.32–7.47 ppm) similar to partial melts derived from a mantle source of dominant spinel lherzolite (fig. 10b). In contrast, the Qiemuerqieke hornblende-bearing



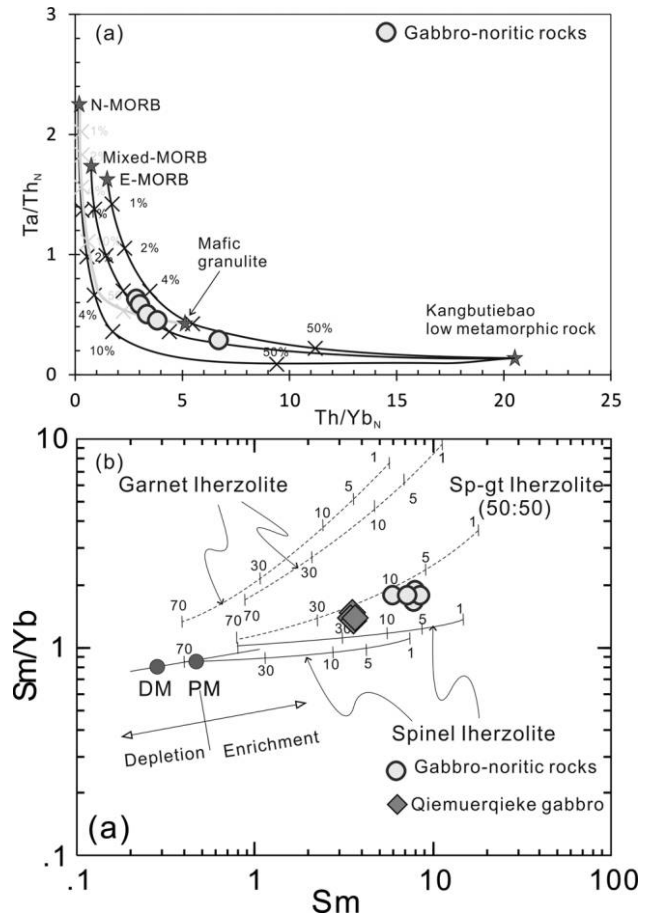
**Figure 9.** Initial  $^{87}\text{Sr}/^{86}\text{Sr}$  versus  $^{143}\text{Nd}/^{144}\text{Nd}$  diagram for the gabbro-noritic and quartz dioritic dikes in the Fuyun region. MORB, mid-ocean ridge basalt. A color version of this figure is available online.

gabbro in the Chinese Altai may be sourced from a relatively shallower mantle source that was also dominated by spinel lherzolites, as suggested by their lowest Sm/Yb ratios (fig. 10b).

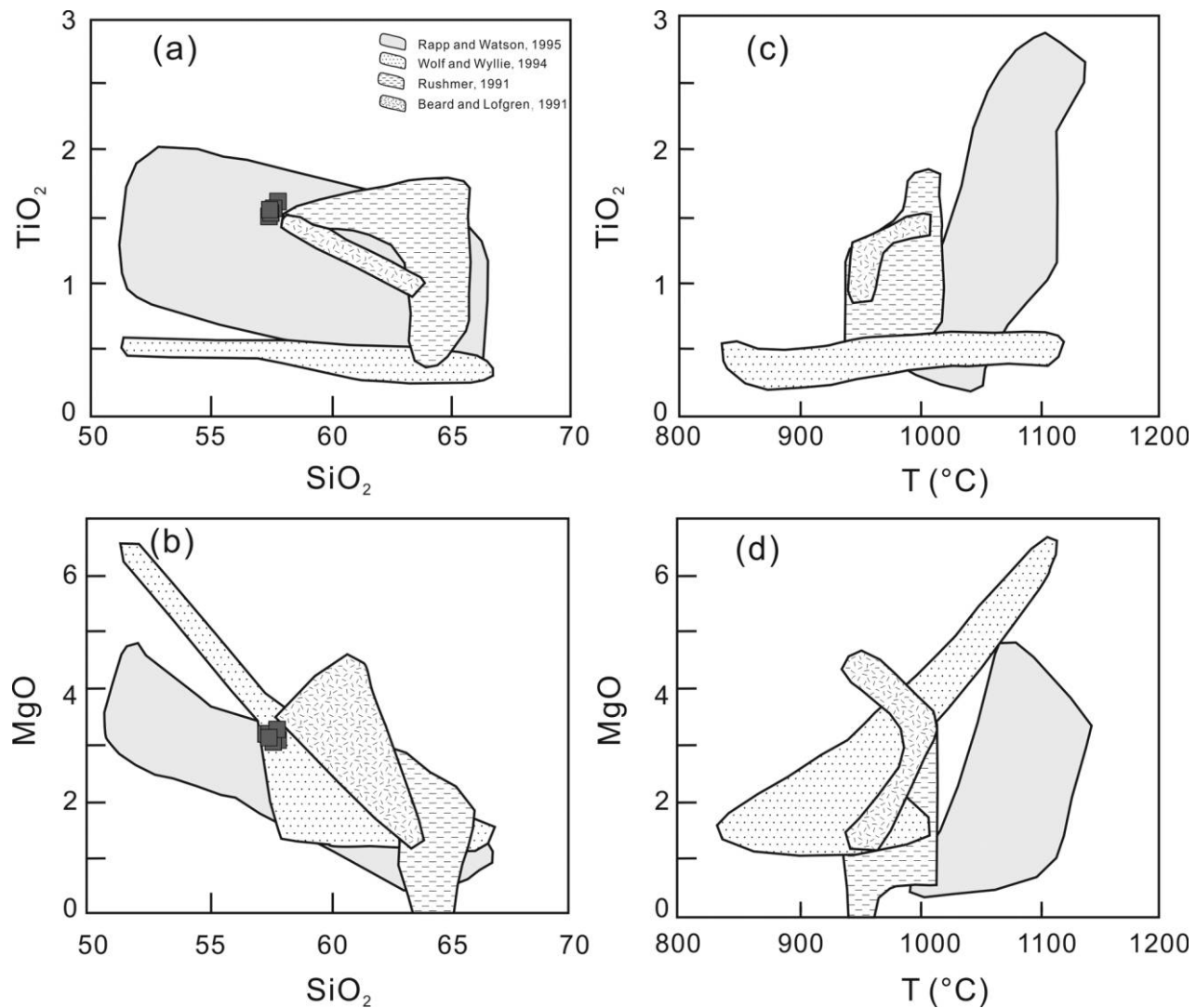
**Petrogenesis and Magma Source of the Quartz Diorites.** Although the quartz diorites were emplaced at 277 Ma, coeval with the gabbro-norites, contrasting isotope compositions and the lack of transitional components do not support the possibility that the quartz diorites are derivatives of the gabbro-norites by fractional crystallization. The quartz diorites have intermediate  $\text{SiO}_2$  (57.3–58.3 wt%) contents and moderately positive  $\epsilon_{\text{Nd}}(t)$  ( $\sim +2.5$ ) and zircon  $\epsilon_{\text{Hf}}(t)$  (+9.1 to +14.4) values, suggesting that their precursor magmas were sourced from a relatively less depleted mantle source or juvenile mafic crust. The restricted  $\text{SiO}_2$  (57.3–58.3 wt%) and the limited variations of MgO contents (3.03–3.13 wt%) indicate that the parental magma may not have been influenced by fractional crystallization and/or crustal contamination. Eichelberger (1978) advocated that andesitic volcanic rock is a mixture of melts from the upper mantle and lower crust. Although the quartz diorites have chemical compositions resembling the andesitic volcanic rocks, there is no solid evidence from petrographic investigations to support magma mixing. In addition, the parental magma is unlikely to be derived from partial melting of oceanic crust, which generally yields adakitic melts with high Sr/Y ratios (e.g., Defant and Drummond 1990). Therefore, we ascribe the parental magma of the quartz diorites to partial melting of juvenile mafic lower crust, because a thick, up to 46-km mafic-intermediate igneous

rock layer exists at the depths of the middle to lower crust (Wang et al. 2003).

Experimental (e.g., Helz 1976; Beard and Lofgren 1991; Rapp et al. 1991; Rushmer 1991; Wolf and Wyllie 1994; Rapp and Watson 1995) and theoretical (e.g., Roberts and Clemens 1993) studies demonstrate that dehydration melting of basaltic rocks within the lower crust with high heat flow can



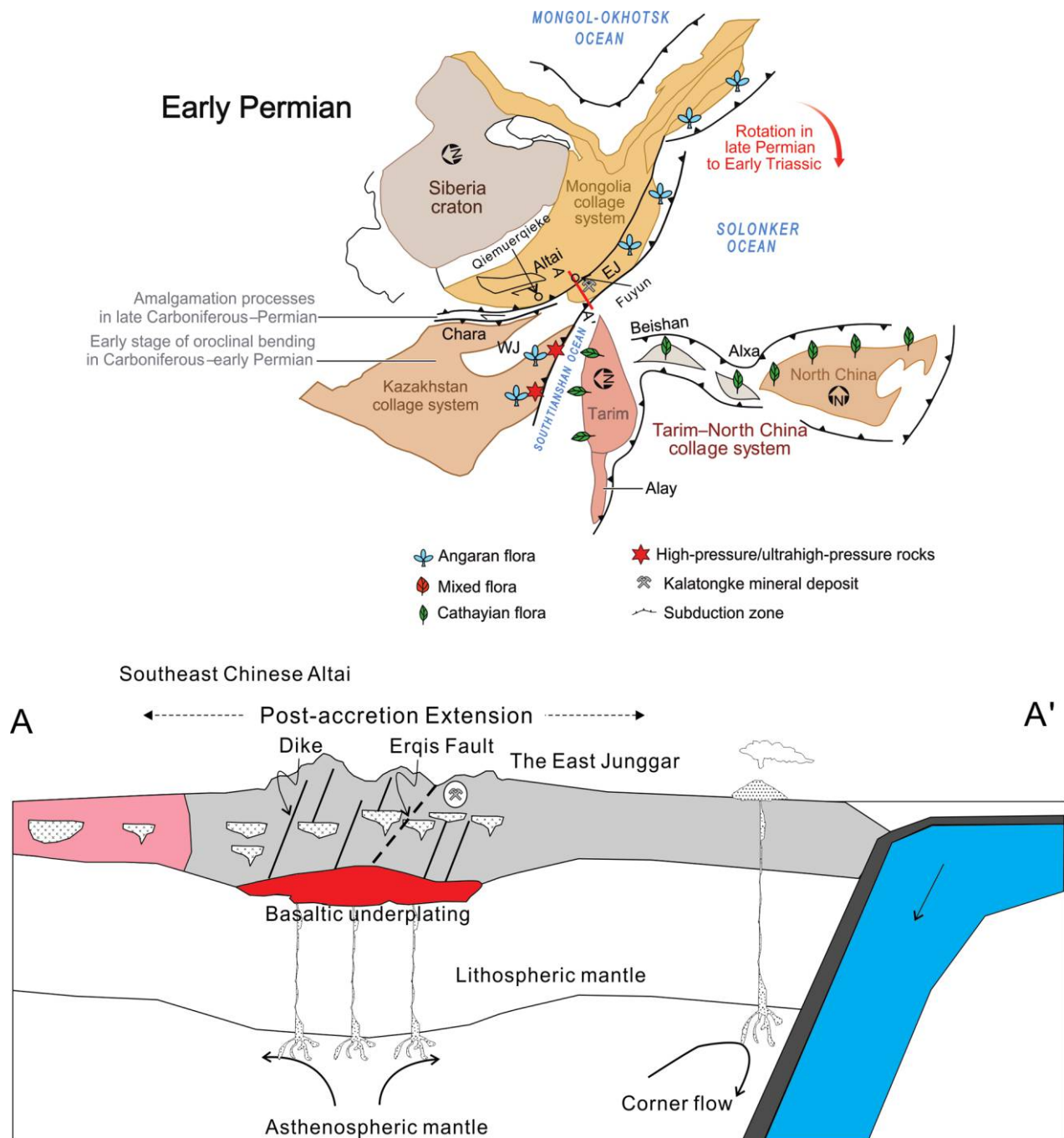
**Figure 10.** *a*,  $(\text{Th}/\text{Yb})_{\text{N}}$  versus  $(\text{Ta}/\text{Yb})_{\text{N}}$  diagram for the gabbro-noritic and quartz dioritic rocks. The curve represents the simple mixing modeling results. Mixing mantle source between normal mid-ocean ridge basalt (N-MORB) and enriched MORB (E-MORB) is considered to be the presumed parental magma, and the Kangbutiebao low metamorphic rock (Long et al. 2007) is used to be a potential crustal contaminant. *b*, Plots of Sm/Yb versus Sm for the gabbro-noritic rocks in the Fuyun region. Mantle array defined by depleted MORB mantle (DM; McKenzie and O'Nions 1991) and primitive mantle (PM; Sun and McDonough 1989). Melting curves for spinel lherzolite ( $\text{Ol}_{53} + \text{Opx}_{27} + \text{Cpx}_{17} + \text{Sp}_{11}$ ) and garnet peridotite ( $\text{Ol}_{60} + \text{Opx}_{20} + \text{Cpx}_{10} + \text{Gt}_{10}$ ) with both DM and PM compositions are after Aldanmaz et al. (2000). Numbers along lines represent the degree of the partial melting. A color version of this figure is available online.



**Figure 11.** Plots of TiO<sub>2</sub> and MgO versus SiO<sub>2</sub> (a, b) and of TiO<sub>2</sub> and MgO versus temperature (c, d) for the Fuyun quartz diorites and experimental investigations. Note that the composition of the quartz diorites is likely reproduced by high-temperature melting of a source similar to the alkali-enriched basaltic rocks of Rapp and Watson (1995).

produce significant volumes of mafic-intermediate melts. Specifically, dehydration melting of amphibolite can give rise to 10%–60% quartz diorite in tonalite melts at temperatures of 900°–1100°C, whereas H<sub>2</sub>O-saturated partial melting can produce similar amounts of granitic melts at lower temperatures, between 850° and 900°C (e.g., Rapp et al. 1991; Wolf and Wyllie 1994; Rapp and Watson 1995). The quartz diorites of this study have chemical compositions overlapping those of partial melts derived from metabasaltic rocks. For instance, they possess medium SiO<sub>2</sub>, high Al<sub>2</sub>O<sub>3</sub>, moderate Na<sub>2</sub>O/K<sub>2</sub>O, high LREE, and moderate HREE concentrations (figs. 6–8). Experimental studies show that garnet generally occurs as a major residual mineral of crustal partial melting at greater depths (>10 kbar; e.g., Rapp et al. 1991;

Wolf and Wyllie 1994; Rapp and Watson 1995), which retains the majority of Y and HREE, resulting in significant deficiencies of such elements in relevant partial melts. As for the quartz diorites of this study, they have high Y (>39.8 ppm) and HREE (Yb >3.64 ppm) concentrations and low Sr/Y ratios (<12), suggesting that dehydration melting should take place at shallow depths at least above the garnet stability field (<10 kbar; e.g., Patiño Douce 1996; Singh and Johannes 1996). The negative Sr and Eu anomalies may be due to plagioclase residue in the magma source, whereas the relatively high TiO<sub>2</sub> contents and insignificant MREE depletion suggest that amphibole was not a residual phase (e.g., Petford and Atherton 1996). Collectively, the chemical compositions of the quartz diorites are consistent with the intermediate liquids



**Figure 12.** Early Permian paleogeographic reconstructions showing simplified plate boundaries and labels of some major features of the Central Asian Orogenic Belt and the postaccretion extensional scenario are illustrated for the southeast Chinese Altai (modified after Xiao et al. 2015).

(quartz dioritic, dioritic), produced by ~40% partial melting of basaltic rocks at  $T = 1050^{\circ}\text{--}1100^{\circ}\text{C}$  and  $P = 8$  kbar with granulite (plagioclase + clinopyroxene  $\pm$  orthopyroxene  $\pm$  olivine) as a residue (Wolf and Wyllie 1994; Rapp and Watson 1995). Moreover, the quartz diorites are characterized by high  $\text{K}_2\text{O}$  (>1.89 wt%), similar to experimental melts produced

by partial melting of alkali basaltic and high-Al basaltic sources (fig. 11) but different from those generated by low K-basaltic rocks (Wolf and Wyllie 1994; Rapp and Watson 1995). On the other hand, the high MgO contents (>3.03 wt%) of the quartz diorites imply that high-Al basaltic sources may be unlikely. In summary, the magma source of the quartz diorites

was likely dominated by alkali-enriched basaltic rock, which may be melted at relatively shallow depths of the lower crust.

Partial melting of the lower crust is generally related to high heat regime. In the south Chinese Altai, 260–280 Ma high-temperature granulites have been reported (Chen et al. 2006b; Tong et al. 2014). *PT* estimates suggest that metapelitic granulite might have undergone peak metamorphic conditions of  $P = \sim 8$  kbar and  $T = \sim 960^\circ\text{C}$  (Tong et al. 2014) and that basic granulite had a peak metamorphic temperature exceeding  $950^\circ\text{C}$  (Li et al. 2010). Moreover, the basic granulites consist mainly of plagioclase, clinopyroxene, and orthopyroxene as well as minor amphibole and biotite (Li et al. 2004), resembling the residue mineral assemblage after partial melting of amphibolites at  $1050^\circ\text{--}1100^\circ\text{C}$  and 8 kbar (e.g., Wolf and Wyllie 1994; Rapp and Watson 1995). These lines of evidence suggest a high geothermal gradient in the south Chinese Altai when the quartz diorites were generated.

***Tectonic Scenario of the South Chinese Altai in the Permian.*** Recent studies have documented that the Chinese Altai is composed mainly of early Paleozoic sedimentary, volcanic, and granitic rocks, similar to a Japan-type island arc (Xiao et al. 2004, 2009, 2015). The intermediate-mafic dikes in our study crop out in the south Chinese Altai, which is dominated by an accreted Silurian–Early Devonian island arc (Sun et al. 2008; Cai et al. 2011c). Zhang et al. (2015) advocated that the island arc was accreted to the main body of the Chinese Altai in the Devonian and jointly underwent multiple shortening events before the crustal-scale sinistral strike-slip shearing along the Erqis fault zone at 290–240 Ma. We note that the South Chinese Altai, as a crucial component of the Mongolia collage system (Xiao et al. 2015), merged with several separate tectonic units involving the West Junggar, Junggar basin, and East Junggar. The temporal and spatial variations (fig. 12) imply that the amalgamation history of the region can be hardly reconciled by a simple tectonic scenario.

In the Fuyun region, where our intermediate-mafic dikes crop out (figs. 1, 2), the East Junggar arc was docked to the Mongolia collage system in the early Permian, and the active margin was changed into a back-arc or intraplate setting. A sequence of tectonic events may have been witnessed by diagnostic structural evidence and distinctive magmatism. The NW-extending intermediate-mafic dikes show an extensional state perpendicular to the strike of Altai orogen in the Permian. This extensional scenario facilitated emplacement of synchronous A-type granites in the region (Han et al. 1997; Briggs et al. 2007; Sun et al. 2009; Tong et al. 2012). In addition, Gao and

Zhou (2013) suggested that magma from an  $\sim 308$  Ma dioritic suite was derived from the thickened crust during the amalgamation of the Chinese Altai with the East Junggar, and a noritic suite in the Kalatongke area subsequently formed from a mantle-derived high-Mg magma as a result of the upwelling of the asthenospheric mantle in a postaccretion environment. Li et al. (2012) related the formation of the Kalatongke intrusions to decompression melting in upwelling of the asthenosphere as a result of slab break-off during a transitional period from oceanic subduction to collision in the early Permian. We should emphasize that the Permian mafic-ultramafic rocks and A-type granites are mainly distributed along the Erqis suture zone, suggesting a relatively thin and weak lithosphere along the deep fault, which is most favorable for magma emplacement (Griffiths and Campbell 1991). For the southeast Chinese Altai (fig. 12), we outline a tectonic evolution that involves a sequence of tectonic scenarios from ocean subduction, terrane amalgamation, and subducting slab break-off to post-accretion extension, which took place in the late Carboniferous to Permian. Owing to amalgamation of the Chinese Altai with the East Junggar, the Mongolian collage system was considerably enlarged, and the active margin likely migrated southward (fig. 12).

## Conclusions

1. The grabbronoritic and quartz dioritic dikes were emplaced at  $276.7 \pm 2.9$  and  $273.2 \pm 4.3$  Ma, respectively, in the southern Chinese Altai. This igneous activity was broadly coeval with the Permian magmatism in the region.
2. Parental magmas of the grabbronorites might have originated from a depleted mantle source dominated by spinel lherzolite. The quartz diorites were likely derived from a juvenile basaltic crust, which may have been closely related to the intraplate and/or underplating of hot mantle-derived magmas.
3. The Permian intermediate-mafic dikes formed in an extensional environment after the amalgamation of the southeast Chinese Altai with the East Junggar.

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