Early Paleozoic collision-related magmatism in the eastern North Qilian orogen, northern Tibet: A linkage between accretionary and collisional orogenesis

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ABSTRACT

Collision-related magmatism in accretionary-to-collisional orogens records a tectonic transition from early subduction-accretionary processes to collisional orogenesis, and also plays a significant role in continental growth. Here, we present an integrated study of field observations, geochemistry, whole-rock Rb-Sr and Sm-Nd isotopes, and zircon U-Pb ages and Lu-Hf isotopes for the Laohushan mafic to felsic magmatic rocks related to initial collision between the Akx terrane and the Central Qilian block along the North Qilian orogenic belt, northeastern Tibet. The Laohushan magmatic rocks are dominated by quartz diorites (ca. 426 Ma), with minor tonalites enclosing dioritic enclaves (ca. 430 Ma) and hornblende xenoliths (ca. 448 Ma), and some coeval dolerite dikes (ca. 427 Ma) intruded into the accretionary complex. The quartz diorites are characterized by light rare earth element (LREE)-enrichment but have high field strength element (HFSE)-depleted patterns and have mostly negative initial εNd (–2.8), near chondritic zircon initial εHf (–0.4 to +1.4) values and an Archean Nd model age (TDM = 2.74 Ga), suggesting that the hornblendites were likely produced by partial melting of subcontinental lithospheric mantle peridotite that was metasomatized by subduction-related melts beneath the Archean–Proterozoic Akx terrane. We propose that partial melting of the lower crust of the early Paleozoic North Qilian orogenic belt was in response to slab breakoff and asthenospheric upwelling during the initial stage of collisional orogenesis. This study demonstrates that heterogeneous magma sources, involving accretionary materials (i.e., accreted oceanic crust and sediments) and various mantle-derived components, were mixed to form the collision-related magmatic rocks. It also highlights the significance of collision-related magmatism in continental growth and stabilization of newly-assembled crust in accretionary-to-collisional orogens.

INTRODUCTION

Convergent continental margins are major sites for crust-mantle interaction, the generation of new continental crust and recycling of older crustal material, with subsequent mass and energy exchange between the crust and upper mantle (Kay and Kay, 1988; von Huene and Scholl, 1991; Rudnick, 1995; Clift et al., 2009; Cawood et al., 2009, 2013; Hawkesworth et al., 2010; Spencer et al., 2017). During these geodynamic processes, large volumes of magmatic rocks (e.g., subduction-related intrusions, syn-accretionary/collisional intrusions, post-accretionary/collisional intrusions) form in different phases of orogenesis (accretionary/collisional) (Dewey, 1988; Barbarin, 1999; Bonin, 2004; Cawood et al., 2009).

Collision-related magmatism is produced during collision of two continents/arcs or between arc and continent (Liégeois, 1998). Generally, collisional phases occurred after subduction and accretionary processes, when the early accreted rocks may contribute to the magmatism as one of its potential crustal sources. Therefore, a study of collision-related magmatism formed in accretionary-to-collisional orogens will help us evaluate the contribution of accreted materials in explaining the petrogenesis and evolution of magmas (Harris et al., 1986; Chung et al., 2005; Li et al., 2016, 2017; Jiang et al., 2016). In addition, collision-related magmas with sources originating from mantle or juvenile crust play a significant role in crustal growth and reworking during collisional orogenesis (Niu et al., 2013; Coulinié et al., 2016). Moreover, the spectrum of processes that produce collision-related magmas, including magmatic underplating and crustal melting, can be very important for the stabilization and homogenization of the anisotropic and thickened continental crust and can provide new constraints on the processes that transform an active orogen into a stabilized continent. Therefore, knowledge about the geological processes that generate collision-related juvenile magmatic rocks can provide important new insights into understanding the evolution of continental crust and the relationship between accretionary and collisional orogenic events.
The Qilian orogenic belt, located in the northeastern Tibetan Plateau (Fig. 1A), records a long evolutionary history from continental breakup, seafloor spreading, oceanic subduction and accretion, finally resulting in continental collision, deep continental subduction, and exhumation (Song et al., 2006, 2013, 2014a, 2015, 2017; Zhang et al., 2007; Xiao et al., 2009). Multiple geodynamic stages are well preserved and provide an excellent natural laboratory for evaluating the connection between accretionary and collisional orogenic stages in a multiphase orogen. In addition, collision-related (syndiagnostic post-collisional) magmatic rocks with juvenile isotopic signatures have been reported from this orogen (Song et al., 2015; Yu et al., 2015; S. Chen et al., 2016b, 2018). However, little attention has been paid to their influence on the evolution of continental crust during the collisional process, or their petrogenetic linkage with the accretionary orogenic stage. Hence, the significance of magmatic rocks derived partially from melted accreted material in the stabilization of orogenic belts needs to be addressed.

In this study, we conducted detailed field observations, petrographic and mineralogical studies, bulk-rock geochemical, and Rb-Sr and Sm-Nd isotopic measurements, of collision-related magmatic rocks from the eastern margin of the North Qilian orogenic belt, northeastern Tibet, to understand the complex magma mixing processes involved in their genesis. With these data we aim to constrain the nature of the magma sources and geodynamic processes involved, and to assess the contribution of collision-related magmatism to continental growth.

**GEOLOGICAL BACKGROUND**

The Qilian orogenic belt, as an important part of the Central China orogenic belt, is bounded by the Tarim craton, Alxa terrane, and North China craton to the north and the Qaidam block and Qilian-Dabie orogen to the south (Fig. 1A) (Song et al., 2005, 2006, 2007, 2009, 2013, 2014a; Zhang et al., 2007; Gong et al., 2016). It is divided into three sub-units that are, from north to south: (1) the North Qilian orogenic belt (NQOB), (2) the Central Qilian block, and (3) the South Qilian orogenic belt (Fig. 1B). The NQOB, alternatively named as the North Qilian accretionary belt (Y.Q. Zhang et al., 2017c; Song et al., 2017), strikes NW-SE and extends for more than 1000 km. The NQOB consists of two ophiolite belts, volcanic and granitic rocks, high pressure (HP) metamorphic rocks, and accretionary complexes and was regarded as a suture zone between the Alxa terrane and the Central Qilian block (Wu et al., 1993; Wang et al., 2005; Song et al., 2007, 2013, 2014a; Zhang et al., 2007; J.X. Zhang et al., 2017a; Y.Q. Zhang et al., 2017c; Wei and Song, 2008; Wei et al., 2009).

The southern ophiolite belt (ca. 550–497 Ma) mainly consists of mantle peridotite, gabbro, normal and enriched middle-ocean-ridge basalts (N-MORB and E-MORB), and pelagic sedimentary rocks, representing upper mantle and oceanic crust fragments of the paleo-Qilian ocean basin (Song et al., 2013). The northern ophiolite belt (ca. 490–448 Ma) comprises ultramafic rocks, cumulates, MORB and supra-subduction zone (SSZ) basalts, and pelagic-hemipelagic siliceous-argillaceous rocks, which were considered to have formed in a back-arc oceanic basin (e.g., Qian et al., 2001; Xia et al., 2003; Song et al., 2013). A Cambrian–Ordovician arc complex (ca. 516–446 Ma), located between the two ophiolite belts, consists of boninitic complexes, felsic calc-alkaline volcanic rocks and some granitoid plutons (Xia et al., 2003; Wang et al., 2005; Wu et al., 2010; Xie et al., 2012; Song et al., 2013). The high pressure-low temperature metamorphic rocks are exposed as several fault-bounded slices within the arc and accretionary complexes and the metamorphic ages of blueschists and eclogites are ca. 489–446 Ma (Song et al., 2004, 2014a; Zhang et al., 2007). Since the Early Silurian, the Central Qilian block collided with the Alxa terrane, producing voluminous syn-collisional/post-collisional magmatic rocks between ca. 430 to 374 Ma (e.g., Tseng et al., 2009; Yu et al., 2015; S. Chen et al., 2016b, 2018; L.Q. Zhang et al., 2017b).

The Central Qilian block mainly consists of Precambrian granitic gneisses and metamorphic rocks (ca. 1000–800 Ma) (Wan et al., 2003), overlain by Paleozoic sedimentary rocks and intruded by granitoids (Huang et al., 2015). The South Qilian orogenic belt, also named the South Qilian accretionary belt, is dominated by Cambrian–Ordovician (ca. 510–480 Ma) volcanic-sedimentary rocks, subduction-accretionary rocks and some Neoproterozoic metamorphic rocks (e.g., Yan et al., 2015; Y.Q. Zhang et al., 2017c; Song et al., 2017; Fu et al., 2018). An ultrahigh pressure (UHP) metamorphic belt (ca. 438–420 Ma) in the northern Qaidam block records a deep continental subduction event (Song et al., 2003, 2004, 2005, 2009, 2014a). The UHP rocks consist of granitic and pelitic gneisses intercalated with blocks of eclogite and ultramafic rocks (Song et al., 2014a). Coesite and diamond inclusions identified in zircon and garnet indicate burial depths of ~100–200 km (Yang et al., 2001; Song et al., 2003, 2004, 2005).

The Laohushan Complex, located in the eastern segment of the northern margin of the NQOB (Fig. 1C), is mainly composed of ophiolitic rocks and accretionary complexes including serpentinitized harzburgite, gabbro, massive and pillow basalts, siliceous-argillaceous rocks, relatively coherent turbidite and incoherent mélanges. The age of a gabbro sheet from the Laohushan ophiolite is constrained as Late Ordovician (448.5 ± 4.7 Ma) by zircon U-Pb isotopic analyses (Song et al., 2013). Some undeformed dolerite dikes intruded into the accretionary complex (Fig. 1E). The volcano-sedimentary complex is intruded by the Laohushan dioritic pluton in the north and is unconformably overlain by Early Devonian molasse and late Paleozoic stable epicontinental sedimentary rocks.

**FIELD GEOLOGY AND PETROLOGY**

The Laohushan pluton strikes NWW-SEE and extends for ~20 km (Figs. 1B–1E). It is dominated by fine- to medium-grained quartz diorite (Figs. 1D and 2A) with minor tonalite in local outcrop. The quartz diorite contains abundant dioritic enclaves or mafic microgranular enclaves (MMEs) and medium-grained hornblende xenoliths (Figs. 2B–2I). The dioritic enclaves are mostly several to tens of centimeters in size and show different shapes, including ellipsoidal, lensoid, or tear drop (Figs. 2B, 2C, and 2F–2H). The contact relationships between quartz diorite and dioritic enclaves are typically gradational (Figs. 2C and 2F–2H) The dioritic enclaves are fine-grained (0.5–1 mm) and exhibit a weak preferred orientation with long axes striking NWW (290–310°). The hornblende xenoliths range from tens of centimeters to several hundreds of meters in size (Figs. 2D, 2E) and their boundaries with the quartz diorite are mostly sharp (Figs. 2D, 2E).

The quartz diorite samples collected for this study are fine- to medium-grained, composed mainly of plagioclase (50%–55%), quartz (15%–20%), amphibole (5%–10%), alkali feldspar (2%–5%), and biotite (2%–5%) (Fig. 3A), and the accessory minerals include apatite, titanite, and zircon. Most minerals are euhedral to subhedral. Plagioclase (0.5–1 mm length) is weakly zoned (Figs. 3B, 3C), with polysynthetic twinning (Fig. 3A). Amphibole occurs as euhedral to subhedral grains, with lengths of 0.5–1 mm (Fig. 3A). Quartz is anhedral and fills the interstices between amphibole and plagioclase crystals (Fig. 3A). Tonalite is fine- to medium-grained and contains quartz (20%–30%), plagioclase (50%–60%), amphibole (15%–25%), and alkali feldspar (5%–7%), with apatite, titanite, and zircon as accessory minerals.

Dioritic enclaves are typically fine-grained (0.2–1 mm) and contain plagioclase (50%–60%), amphibole (10%–20%), quartz (2%–5%), biotite (1%–3%), and alkali feldspar (2%–5%), with accessory minerals of magnetite, apatite,
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Figure 1. (A) Digital elevation map (DEM) showing the distribution of major cratons and orogens in China. DEM prepared from the NASA Shuttle Radar Topography Mission data of the U.S. Geological Survey’s EarthExplorer (https://earthexplorer.usgs.gov/). (B) Simplified geological map of the Qilian orogenic belt showing the distribution of early Paleozoic granite and volcanic rocks (modified from 1:1,000,000 geological map of Kunlun and surrounding areas). (C) Schematic geological map of the Laohushan area, eastern section of the North Qilian orogenic belt (modified from 1:200,000 geological map of Yongtai area). (D) Detailed geological map showing the distribution and composition of the Laohushan pluton and sample locations. (E) Schematic cross section showing the field relationship between the Laohushan pluton and the accretionary complex. Zircon U-Pb ages in Figure 1B are from the following references: magmatic rocks in the Alxa terrane are from Liu et al. (2016); magmatic rocks in the North Qilian orogenic belt are from Tseng et al. (2009); Wu et al. (2010); Chen et al. (2014); Yu et al. (2015); L.Q. Zhang et al. (2017b); and magmatic rocks in the Central Qilian block are from Cowgill et al. (2003); Gehrels et al. (2003); Su et al. (2004); Li et al. (2010); Huang et al. (2015).

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Figure 2. Field photographs showing different rock types from the Laohushan pluton, their contact relationships and the intrusive relationship of a dolerite dike. (A) Fine- to medium-grained quartz diorite. Pen is 14 cm long. (B) Dioritic enclaves within quartz diorite. Pen is 14 cm long. (C) Teardrop shaped dioritic enclave within quartz diorite with a gradational boundary between them. Pen is 14 cm long. (D, E) Different shapes and sizes of hornblendite xenoliths in quartz diorite, showing their sharp boundaries. Hammer is 35 cm long and the diameter of hammer handle is 3 cm. (F–I) Different shapes of dioritic enclaves with feldspar megacrysts and the irregular boundary between quartz diorite and dioritic enclaves. Pen head is 3 cm long, pen is 14 cm long and hammer is 35 cm long. (J) Dolerite dike crosscutting basalt within the accretionary complex. Pen is 14 cm long.
Figure 3. Photomicrographs and backscattered electron (BSE) images illustrating the petrographic characteristics of different rocks from the Laohushan pluton and the coeval mafic dikes. (A) Photomicrograph of medium-grained quartz diorite. (B, C) Plagioclase megacrysts (Line01 and Line04, Table DR1, see footnote 1) within dioritic enclave showing core-mantle-rim compositional zoning. An—Anorthite. (D) Fine-grained dioritic enclave. (E) Plagioclase megacryst in dioritic enclave rimmed by amphiboles. (F) Plagioclase megacryst in dioritic enclave showing poikilitic texture with plagioclase crystal containing amphibole, apatite, and zircon inclusions. (G) BSE image showing acicular apatite in plagioclase megacryst from dioritic enclave. (H) Amphiboles in dioritic enclave. (I) Bent biotite megacryst in dioritic enclave rimmed by amphiboles and containing some apatite inclusions. (J, K) Photomicrograph showing massive hornblende with amphibole and clinopyroxene crystals. (L) Fine-grained dolerite dike with ophitic texture. Mineral abbreviations according to Whitney and Evans (2010): Qz—quartz; Pl—plagioclase; Bi—biotite; Amp—amphibole; Ap—apatite; Cpx—clinopyroxene.
titane, allanite, and zircon (Fig. 3D). Plagioclase crystals are subhedral to anhedral and show a range in size. Some plagioclase megacrysts are rimmed by amphiboles (Fig. 3E) and contain acicularapatite and anhedral amphibole inclusions (Figs. 3F, 3G). Amphibole is present as euhedral to subhedral grains (Fig. 3H). Biotite megacrysts are also rimmed by fine-grained amphiboles and contain inclusions of apatite and zircon (Fig. 3I).

The hornblende xenoliths are dominated by medium- to coarse-grained amphibole (80%–90%) and clinopyroxene (5%) (Figs. 3J, 3K), with rare biotite, and show cumulative characteristics.

The dolerite dikes intruding the accretionary complex (Fig. 1E) are fine-grained (0.2 mm), displaying a typical ophitic texture with fine-grained pyroxene grains (~20%) occurring within euhedral lath-shaped plagioclase crystals (~60%) (Fig. 3L). Some pyroxene grains have been altered to amphibole.

**Analitical Methods**

Fifteen samples from different rock types including six quartz diorites, two tonalites, three dioritic enclaves, two hornblende xenoliths, and two dolerite dikes from the Laohushan area were analyzed. Of these: ten samples were analyzed for mineral compositions; fifteen samples were analyzed for whole-rock major and trace elements; five samples (one quartz diorite, two dioritic enclaves, one hornblende, and one dolerite dike) were prepared for zircon U-Pb dating and Lu-Hf isotopic analysis; and nine samples were analyzed for Rb-Sr and Sm-Nd isotopic compositions.

**Mineral Major Elements**

Mineral chemical compositions were determined at the Center for Global Tectonics, School of Earth Sciences, China University of Geosciences Wuhan (CUG) using a JEOL JXA-8230 electron microprobe. The accelerating voltage was 15 kV, with a beam current of 20 nA and beam diameter of 3 µm. The background counting time was 5 s. Data were corrected online using a modified ZAF atomic number, absorption, and fluorescence correction procedure. The calibration standards for elements were albite (Na), orthoclase (K), diopside (Si, Mg, Ca), yttrium-aluminum garnet (Al), magnetite (Fe), apatite (P), and rutile (Ti). Analytical errors were generally less than 2%.

**Whole-Rock Major and Trace Elements**

Major and trace element measurements were carried out at the State Key Laboratory of Geological Processes and Mineral Resources (GPMR), at CUG. The samples were crushed in a jaw crusher, with 30 g sub-samples ground in an agate mill to 200-mesh. Major oxides were analyzed using an X-ray fluorescence spectrometer, with analytical precision better than 5%. Loss on ignition was measured after heating to 1000 °C. Trace elements were determined by inductively coupled plasma–mass spectrometry (ICP-MS) using an Agilent 7700e system, with analytical precision better than 5%. Detailed sample-digestion and analytical procedures for trace element analyses are the same as described by Liu et al. (2008).

**Zircon U-Pb Dating**

Samples for zircon dating were crushed, elutriated first and then zircon grains were separated by magnetic and heavy liquid methods. Representative zircons with good crystal shapes were selected by handpicking under a binocular microscope. The selected grains were embedded in epoxy resin and polished to half their thickness. Transmitted and reflected light photomicrographs, and cathodoluminescence (CL) images were taken at GPMR, at CUG. The CL images were obtained using a Gatan Mono CL4+ instrument installed on a Quantax 450 FEG scanning electron microscope (SEM).

Zircon U-Pb isotope analyses were performed at the LA-ICP-MS laboratory of GPMR, at CUG, using an instrument of Geos-2005 laser ablation system, coupled with an Agilent 7500a ICP-MS instrument. Detailed operating conditions of the instrument are the same as described by Liu et al. (2008). Zircon 91500 as the external standard was analyzed twice every five analyses. Time-dependent drifts of U-Th-Pb isotopic ratios were corrected using a linear interpolation for every five analyses according to the variations of 91500 (Liu et al., 2008). National Institute of Standards and Technology SRM 610, as the external standard for concentration calculation, was measured twice every 20 sample spots. Zircon standard GJ-1, as the unknown, was measured twice every 20 sample spots. Off-line selection and integration of background and analyte signals, time-drift correction, and quantitative calibration were performed using ICPMSDataCal (Liu et al., 2007). Zircon U-Th-Pb ratios were calculated using the Isoplot/Ex version 3.0 software (Ludwig, 2003).

**Zircon Lu-Hf Isotopes**

In situ zircon Lu-Hf isotopic analyses were conducted at the GPMR, at CUG, using a Neptune Plasma multicollector–inductively coupled plasma–mass spectrometer (MC-ICP-MS) (Thermo Fisher Scientific, Germany) in combination with a Geolas 2005 excimer ArF laser ablation system (Lambda Physik, Göttingen, Germany). Detailed instrumental conditions for the laser ablation system and the MC-ICP-MS and analytical methods are the same as described by Hu et al. (2012). The beam diameter was 44 µm and each measurement consisted of 20s of acquisition of the background signal followed by 50s of ablation signal acquisition. The 176Yb/177Yb and 186Lu/176Yb ratios of 0.79639 (Fisher et al., 2014) and 0.02656, respectively, (Blichert-Toft et al., 1997) were used to correct the interference of 176Yb on 176Hf and 176Lu on 176Hf. To correct the mass bias of Hf (JHF) and Yb (JYb), an exponential correction was used to normalize the ratios of 176Hf/176Yb and 177Yb/177Yb to 0.7325 and 1.13685, respectively (Fisher et al., 2014). Off-line selection and integration of analyzed signals, and mass bias calibrations were performed using ICPMSDataCal (Liu et al., 2010). Standard zircons (TEMORA, GJ-1, and 91500) were analyzed after every eight unknowns.

**Whole-Rock Rb-Sr and Sm-Nd Isotope Analyses**

Whole-rock samples were analyzed for Rb-Sr and Sm-Nd isotopic compositions at the GPMR, at CUG. Approximately 50 mg of powder was dissolved in a mixture of concentrated HNO3, HF, and HClO3. Strontium, Nd, and other LREE were separated using standard chromatographic columns with AG50W-X8 and di-(2-ethylhexyl) phosphoric acid (also known as HDEHP) resins, following the procedure of Li et al. (2012). Strontium and Nd isotopic compositions were measured on the Nu Plasma MC-ICP-MS. 146Nd/144Nd was corrected for mass fractionation by normalizing to 146Nd/144Nd = 0.7219 and 87Sr/86Sr ratios were normalized to 86Sr/88Sr = 0.1194. The international standards NBS-987 and JNd-1 were measured to evaluate instrument stability during the data collection stage. The measured values for the BCR-2 Nd and BCR-2 Sr standards were 146Nd/144Nd = 0.512640 ± 0.000011 and 87Sr/86Sr = 0.705029 ± 0.000008, respectively. The measured values of the JNd-1 Nd standard and NBS-987 standard were 146Nd/144Nd = 0.5121208 ± 0.000013 (2σ, n = 5) and 87Sr/86Sr = 0.710241 ± 0.000014 (2σ, n = 3), respectively.

**RESULTS**

**Mineral Compositions**

The composition of the major minerals (plagioclase, amphibole, biotite) in the rocks from
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Figure 4. (A, B) An-Ab-Or diagrams showing the composition of plagioclase in the quartz diorite and dioritic enclaves, respectively. (C) Mg# versus Si diagram showing the classification of hornblendes from quartz diorite, dioritic enclaves, and hornblende xenoliths of the Laohushan pluton according to the nomenclature of Leake et al. (1997). Ab = 100*Na/(Na+K+Ca), An = 100*Ca/(Na+K+Ca), Or = 100*K/(Na+K+Ca), An—anorthite, Ab—albite, Or—orthoclase.

the Laohushan pluton are listed in GSA Data Repository Table DR1 and shown in Figure 4.

**Plagioclase**

The composition of plagioclase crystals in quartz diorite show a range from An$_{55}$ to An$_{37}$ and plot in the range of high-oligoclase to high-andesine (Fig. 4A), whereas most of the An values (An$_{c Autosomal DNA-primed fourier transform (FT) microscopy. Microscopy showed healed (V-shaped) cracks with varying orientations, some of which were parallel to 0160G. A small-scale mesostructure at 0200G is interpreted. Microscopy analysis is performed by X-ray diffraction (XRD) at 0230G. Lattice planes (002), (004), and (006) are clearly visible in the transition to 0260G. The crystal structure of 0270G is analyzed using a combination of XRD and electron microscopy. The resulting information shows that the mineral exhibits a cubic crystal system with unit cell parameters of 0280G. The structure of 0290G is further refined using a crystallographic software package. The refined lattice parameters are 0300G. The structure is confirmed by a series of 0310G that lie in the range of 0320G. A space group analysis reveals that the mineral belongs to the orthorhombic system. The space group is determined to be 0330G. The mineral is confirmed to be a member of the pyroxene group, specifically ortho-pyroxene.

**Major and Trace Elements**

The quartz diorite samples show moderate variations in SiO$_2$ (57.6–62.4 wt%), Na$_2$O (2.7–3.5 wt%), K$_2$O (1.3–2.7 wt%), MgO (2.7–4.7 wt%), and FeO (0.22–0.38) to a much greater extent than the quartz diorites (Table DR2). The rocks have high SiO$_2$ contents (e.g., Nb, Ta, and Ti) and are depleted in HFSEs (e.g., Nb, Ta, and Ti) (Nb/Nb* = 0.07–0.30, Ta/Ta* = 0.13–0.50). The tonalite samples have high SiO$_2$ (67.2–67.8 wt%) and Na$_2$O (3.8–3.9 wt%), K$_2$O (1.15–1.17 wt%), and Al$_2$O$_3$ (17.5–17.6 wt%) contents. The HREEs (Gd/Yb) values are 0.71–0.90. On the primitive mantle-normalized multi-element diagram (Fig. 6B), they show enrichment in LIL elements (e.g., Rb, K, Th, U, and Pb) and are depleted in HFSEs (e.g., Nb, Ta, and Ti) (Nb/Nb* = 0.07–0.30, Ta/Ta* = 0.13–0.50).

**Amphiboles**

Amphiboles show a similar range of compositions in the quartz diorite and dioritic enclaves, whereas they are different in the hornblende xenoliths. According to the nomenclature of Leake et al. (1997), amphiboles in the quartz diorite and dioritic enclaves are classified as magnesio-hornblende (Fig. 4C), with relevant parameters of Mg# = 57–75, Ti = 0.02–0.13, and Al$^{IV}$ = 0.8–1.6 in the quartz diorite and Mg# = 60–76, Ti = 0.02–0.10, and Al$^{IV}$ = 0.3–1.7 in the dioritic enclaves. Amphiboles from hornblende show a much wider range in composition and are classified as magnesio-hornblende to actinolite (Fig. 4C). They have Mg# ranging from 73 to 91, Ti (0.01–0.13), and Al$^{IV}$ (0.1–3.1) values display large variations (Table DR1).

**Biotite**

Biotite crystals show similar compositions in the quartz diorite (MgO = 11.5–12.7 wt%, FeO = 16.2–19.0 wt%, Al = 1.3–1.4 wt%), and Mg# (48.2–50.1) values are lower than those of the hornblende xenoliths (Table DR2). The MgO (1.1–1.2 wt%) and Mg# (48.2–50.1) are lower than those of the quartz diorites and two samples plot as granodiorite (Fig. 5A) on the (Na$_2$O+K$_2$O)-CaO vs SiO$_2$ diagram and have a calcic affinity (Fig. 5B). According to the mineral compositions, they plot as tonalite on the Q’-F-AnOr diagram (not shown, Streckeisen and LeMaitre, 1979). They have low FeO (2.1–2.2 wt%) and plot in the calc-alkaline series on the AFM diagram (Fig. 5B). The A/CNK (molar Al$_2$O$_3$/[CaO+Na$_2$O+K$_2$O]) values are 1.0, plotting in the peraluminous field (Fig. 5D). The Sr contents of the tonalite are lower than those of the quartz diorites and they are enriched in LREE (La/Sm = 4.44–4.86) and depleted in HREE (Gd/Yb = 1.35–1.90), with moderately positive Eu (Eu/Eu* = 1.40–1.64) anomalies (Fig. 6A). They are enriched in LILE (Rb, Th, U, K, Pb) and depleted in HFSEs (Nb, Ta, and Ti) (Nb/Nb* = 0.11–0.12, Ta/Ta* = 0.22–0.38) to a much greater extent than the quartz diorite (Fig. 6B).

The dioritic enclaves are characterized by low SiO$_2$ (48.3–50.7 wt%), Na$_2$O (2.4–4.1 wt%), and...
K₂O (1.5–2.1 wt%) and plot as gabbro and monzogabbro (Table DR2; Fig. 5A), with compositions ranging from calc-alkaline to alkaline series (Fig. 5B). Although they have SiO₂ contents similar to gabbroic compositions (<53 wt%), we name them as dioritic enclaves based on the following concerns: (1) most of the An values (An₅₂–An₂₇) of plagioclase from the enclaves are lower than those of gabbros (>50) (Fig. 4B) and (2) microscopically, the dark minerals of the enclaves are dominantly amphibole and biotite without any pyroxene. They have higher FeOt (7.7–9.7 wt%), MgO (3.2–7.1 wt%), Mg# (41–57), Cr (49–375 ppm), and Ni (16–114 ppm) than the quartz diorites (Table DR2), and plot in the calc-alkaline field on the AFM diagram (Fig. 5C). The dioritic enclaves show variable enrichment in LREE (La/Smᵦ = 1.53–6.91) and are depleted in HREE (Gd/Ybᵦ = 1.35–1.85) and display weak negative to no Eu anomalies (Eu/Eu* = 0.65–1.01) (Fig. 6C). On the primitive mantle-normalized trace element diagram, the dioritic enclaves are enriched in LILE (Rb, Ba, K, and Pb) and show negative anomalies of HFSE (Nb, Ta, and Ti) (Nb/Nb* = 0.12–0.21, Ta/Ta* = 0.16–0.27) (Fig. 6D).

The hornblende xenoliths have high MgO (17.4–19.1 wt%), Cr (674–747 ppm), and Ni (94–149 ppm) contents and high Mg#, Table DR2. They have low SiO₂ (50.6–52.2 wt%), Al₂O₃ (4.5–5.4 wt%), Na₂O (0.57–0.57 wt%), and K₂O (0.15–0.16 wt%) and plot as gabbro or gabbrodiorite (Fig. 5A). They have a narrow range of FeOt (10.6–11.0 wt%) and show a tholeiitic affinity (Fig. 5C). They have lower ΣREE (29.5–34.4 ppm) than the quartz diorites (ΣREE = 41.5–118.6 ppm) and the dioritic enclaves (ΣREE = 64–195 ppm) and exhibit flat REE patterns (La/Smᵦ = 0.91–1.39; Gd/Ybᵦ = 1.27–1.30) with weak negative Eu anomalies (Eu/Eu* = 0.76–0.83) (Fig. 6C). They are enriched in Th, U, and Pb and depleted in Nb, Ta, Sr, and Ti (Nb/Nb* = 0.27–0.41, Ta/Ta* = 0.39–0.55) (Fig. 6D).

The dolerite dike samples have low SiO₂ (47.6–52.8 wt%) and high contents of Cr (474–528 ppm), Ni (326–367 ppm), and Mg# (71–72) (Table DR2) and plot as gabbro or gabbrodiorite.
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Figure 6. (A) Chondrite-normalized rare earth element (REE) patterns for quartz diorites and tonalites; (B) Primitive mantle normalized multi-element diagrams for quartz diorites and tonalites; (C) Chondrite-normalized REE patterns for dioritic enclaves, hornblendites xenoliths and dolerite dikes; (D) Primitive mantle normalized multi-element diagrams for dioritic enclaves, hornblendites and dolerite dikes. The gray shaded fields indicate the composition ranges between middle and lower continental crust. Middle and lower continental crust compositions are from Rudnick and Gao (2003). Chondrite, primitive mantle, normal mid-ocean-ridge basalt (N-MORB), enriched mid-ocean-ridge basalt (E-MORB), and ocean-island basalt (OIB) compositions are from Sun and McDonough (1989).

Zircon U-Pb Ages and Lu-Hf Isotopes

Laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) zircon isotope data for single spot analyses and in situ zircon Lu-Hf analyses are listed in Tables DR3 and DR4 (see footnote 1), respectively. Zircon cathodoluminescence (CL) images and zircon U-Pb concordia diagrams are shown in Figures 7 and 8, respectively. Initial \( \epsilon_{Hf} \) values of the dated zircons were calculated using their U-Pb ages. The plots of initial \( \epsilon_{Hf} \) values versus U-Pb ages and histograms of \( \epsilon_{Hf}(t) \) values for zircons from quartz diorite, dioritic enclaves, hornblendite xenoliths and dolerite dikes are presented in Figure 9.

Most zircon grains from the host quartz diorite (sample QLS10-1) are euhedral to subhedral prismatic with oscillatory zoning, characteristic of magmatic crystallization (Fig. 7A) (Corfu et al., 2003), although some grains show evidence of minor recrystallization. The crystal lengths range from 150 to 200 µm, with length to width ratios of 2:1–3:1. They have 228–919 ppm Th and 336–1105 ppm U, yielding Th/U ratios of 0.47–0.85. A total of 25 spots were analyzed and, with one exception, the analyses yield concordant \(^{206}\text{Pb}^{/^{238}}\text{U} \) ages ranging from 456 to 419 Ma. Among the 24 analyses, four grains yield relatively older concordant \(^{206}\text{Pb}^{/^{238}}\text{U} \) ages (456–441 Ma), which may represent the ages of inherited zircons, whereas the 20 remaining zircons yield concordant \(^{206}\text{Pb}^{/^{238}}\text{U} \) ages (434–419 Ma), with a weighted mean age of 426 ± 2 Ma (Fig. 8A). Sixteen zircon grains were analyzed for Lu-Hf isotopes and the \(^{176}\text{Hf}^{/^{177}}\text{Hf} \) ratios (0.282587–0.282689) show a narrow range, with initial \( \epsilon_{Hf} \) values of +3.0 to +6.2 and two-stage Hf model ages \( t_{DM} \) of 942–1132 Ma (Table DR4; see footnote 1; Fig. 9A).

Zircons from dioritic enclave (sample QLS11-1) are relatively stubby grains with a range of...
Figure 7. Cathodoluminescence (CL) images showing internal structures of representative zircons from (A) quartz diorite (QLS10-1); (B, C) dioritic enclaves (QLS11-1, QLS11-3); (D) Hornblendite xenolith (QLS12-2-1); and (E) dolerite dike (QLS06-1) from the Laohushan pluton in the eastern margin of North Qilian orogenic belt, north-eastern Tibet. Small circles represent the U-Pb analysis sites and the larger circles are the multicollector–inductively coupled plasma–mass spectrometry Hf isotopic analysis sites. Numbers are the ages and initial $\varepsilon_{Hf}$ values as presented in Tables DR3 and Table DR4 (see footnote 1).
Figure 8. Zircon U-Pb concordia diagrams and age histograms for (A) quartz diorite (QLS10-1); (B) dioritic enclave (QLS11-1); (C) dioritic enclave (QLS11-3); (D) hornblendite xenolith (QLS12-2-1); (E) concordia plot and the U-Pb age probability diagram of total zircon data from the dolerite dike (QLS06-1); and (F) younger population in the dolerite dike. MSWD—mean square weighted deviation.
internal structures (Fig. 7B). Most zircon grains are equi-dimensional and euhedral to subhedral, with sizes ranging from 100 to 150 µm and their length to width ratios range from 1:1–2:1. The CL images reveal that most zircons show oscillatory zoning (Fig. 7B), and several have core-rim structures with the cores exhibiting weak zoning and the rims exhibiting broad zoning (Fig. 7B). They have moderate to high Th/U (0.52–0.99) ratios. Twenty-nine grains were analyzed and excluding one outlier, they yield concordant 206Pb/238U ages (436–426 Ma), with the ages of zircon cores ~5–10 m.y. older than those of the rims (Table DR3 [see footnote 1]). Twenty-eight analyses yield a weighted mean age of 431 ± 2 Ma (Fig. 8B). Eleven zircons were selected for Lu-Hf analyses and have a narrow range of 176Hf/177Hf ratios (0.282625–0.282670) and positive initial εHf values (+4.0 to +5.9), resulting in 811–883 Ma one-stage Hf model ages (TDM1) and 968–1065 Ma two-stage Hf model ages (TDM2) (Table DR4; Fig. 9A).

Most zircon grains from dioritic enclave (sample QLS11-3) are euhedral (80–200 µm)
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and have complex internal structures (Fig. 7C). Most zircons are oscillatory zoned (Fig. 7C), although some have core-rim structures (Fig. 7C). They have variable Th/U (0.39–1.01) ratios. Twenty-three analyses were carried out and yield three groups of ages (Table DR3; Fig. 8C). One grain has a 206Pb/238U age of 938 Ma and two cores have concordant 206Pb/238U ages of 447–446 Ma (Fig. 8C). The remaining twenty grains have concordant ages of 435–427 Ma and yield a weighted mean age of 430 ± 2 Ma (Fig. 8C). The 176Hf/177Hf ratios of thirteen zircons vary from 0.282519 to 0.282644 and have positive initial εHf values (+3.9 to +4.8) and single-stage Hf model ages range from 1008 to 1089 Ma (Table DR4).

Zircons from the hornblendite xenolith (sample QLS12-2-1) are euhedral with elongated prismatic shapes and their CL images reveal broad magmatic zonation (Fig. 7D) typical of mafic rocks. They range in size from 100 to 200 µm, with length to width ratios of 2:1–4:1. They show a wide range of Th (296–2168 ppm) and U (429–1640 ppm) contents, yielding high Th/U ratios (0.63–1.32). A total of 20 spots were analyzed and all of the analyses yield concordant 206Pb/238U ages ranging from 453 to 445 Ma, with a weighted mean age of 448 ± 2 Ma (Fig. 8D). Eight zircons record a narrow range in 206Pb/238U ratios (0.282500–0.282542), with initial εHf of –0.4 to +1.4 (Fig. 9A). The single-stage Hf model ages range from 1008 to 1089 Ma (Table DR4).

Zircons from the dolerite dike (sample QLS06-1) are mostly stubby crystals that range in size from 50 to 100 µm, with length to width ratios of 1:1–2:1 and are subhedral to euhedral. The CL images reveal oscillatory, sector, and patchy zonation (Fig. 7E). They have a range of Th (153–459 ppm) and U (346–835 ppm) contents, resulting in Th/U ratios of 0.44–0.84. A total of 20 sites were analyzed and all yielded concordant 206Pb/238U ages ranging from 1639 to 420 Ma with several age groups (Fig. 8E). The dominant group yielded young ages defining a weighted mean 206Pb/238U age of 427 ± 3 Ma (Fig. 8F). The older zircons are interpreted as xenocrysts entrapped by the dikes as it was emplaced in the crust. The 176Hf/177Hf ratios of eight zircons vary from 0.282073 to 0.282911 and yield three distinct groups of initial εHf values. Group 1 with zircon ages of 431–424 Ma have weakly positive initial εHf values (+3.9 to +4.8) and single-stage Hf model ages of 887–848 Ma. Group 2 with zircon ages of 447–425 Ma have extremely high positive initial εHf values (+13.9 to +14.3) and younger Hf model ages (480–502 Ma). Group 3 is represented by one zircon grain with an age of 449 Ma that yielded a negative initial εHf value of −15.1 (Table DR4; Fig. 9A) and an older (1658 Ma) single-stage Hf model age.

Rb-Sr and Sm-Nd Isotopes

Whole-rock Rb-Sr and Sm-Nd isotopic compositions of the quartz diorite, tonalite, dioritic enclaves and hornblendite xenoliths are given in Table DR5 (see footnote 1) and Figure 10. Initial 87Sr/86Sr and εNd values were calculated from previous studies are plotted for comparison in (B). Data sources: Syn-collisional granitoid (ca. 430 Ma) are from S. Chen et al. (2015, 2016b, 2018) and Yu et al. (2015); island-arc volcanic rocks are from Wang et al. (2005); basalts from the Laohushan area are from Qian et al. (2001); dolerite dikes at the southern margin of the Alxa terrane are from Duan et al. (2015); and Qilian eclogites and blueschists are from L. Zhang et al. (2016b). The isotopic compositions for global subducted sediments (Gloss) (Plank and Langmuir, 1998), depleted mantle (DM) (Workman and Hart, 2005), lower continental crust (LCC) (Rudnick and Gao, 2003), and basalt sample (LHS2) from the Laohushan area (Qian et al., 2001) were recalculated to 430 Ma with the values listed below. Gloss: εNd(T) = −5.37, 87Sr/86Sr = 0.714309, 143Nd/144Nd = 0.511809, Rb = 57.2 ppm, Sr = 327 ppm, Sm = 5.78 ppm, Nd = 27 ppm; DM: εNd(T) = 6.52, 87Sr/86Sr = 0.70252, 143Nd/144Nd = 0.512418, Rb = 0.05 ppm, Sr = 7.664 ppm, Sm = 0.239 ppm, Nd = 0.581 ppm; LCC: εNd(T) = −25.87, 87Sr/86Sr = 0.70946, 143Nd/144Nd = 0.51076, Rb = 11 ppm, Sr = 348 ppm, Sm = 2.8 ppm, Nd = 11 ppm; basalt sample (LHS2): εNd(t) = +2.79, 87Sr/86Sr = 0.70487, 143Nd/144Nd = 0.51223. CHUR—chondritic uniform reservoir.

Figure 10. Plots of (A) εNd(t) versus Age (Ga) and (B) εNd(t) versus 87Sr/86Sr for the quartz diorite, dioritic enclave, and hornblendite xenolith and dolerite dike samples from the Laohushan pluton. Sr-Nd isotopic data from previous studies are plotted for comparison in (B). Data sources: Syn-collisional granitoid (ca. 430 Ma) are from S. Chen et al. (2015, 2016b, 2018) and Yu et al. (2015); island-arc volcanic rocks are from Wang et al. (2005); basalt from the Laohushan area are from Qian et al. (2001); dolerite dikes at the southern margin of the Alxa terrane are from Duan et al. (2015); and Qilian eclogites and blueschists are from L. Zhang et al. (2016b). The isotopic compositions for global subducted sediments (Gloss) (Plank and Langmuir, 1998), depleted mantle (DM) (Workman and Hart, 2005), lower continental crust (LCC) (Rudnick and Gao, 2003), and basalt sample (LHS2) from the Laohushan area (Qian et al., 2001) were recalculated to 430 Ma with the values listed below. Gloss: εNd(T) = −5.37, 87Sr/86Sr = 0.714309, 143Nd/144Nd = 0.511809, Rb = 57.2 ppm, Sr = 327 ppm, Sm = 5.78 ppm, Nd = 27 ppm; DM: εNd(T) = 6.52, 87Sr/86Sr = 0.70252, 143Nd/144Nd = 0.512418, Rb = 0.05 ppm, Sr = 7.664 ppm, Sm = 0.239 ppm, Nd = 0.581 ppm; LCC: εNd(T) = −25.87, 87Sr/86Sr = 0.70946, 143Nd/144Nd = 0.51076, Rb = 11 ppm, Sr = 348 ppm, Sm = 2.8 ppm, Nd = 11 ppm; basalt sample (LHS2): εNd(t) = +2.79, 87Sr/86Sr = 0.70487, 143Nd/144Nd = 0.51223. CHUR—chondritic uniform reservoir.
using the reference ages of 426 Ma, 430 Ma, 448 Ma, and 427 Ma for the quartz diores, dioritic enclaves, hornblendite xenoliths, and dolerite dikes, respectively. The quartz diores have a range of initial $^{187}$Os/$^{188}$Os (0.706742–0.707878) ratios and the one tonalite sample has a similar initial $^{187}$Os/$^{188}$Os (0.707242) value to that of the quartz diores. The dioritic enclaves have initial $^{187}$Os/$^{188}$Os ratios of 0.706609–0.707627, whereas the hornblendite has an initial $^{187}$Os/$^{188}$Os value of 0.707305. The dolerite dikes have relatively lower initial $^{187}$Os/$^{188}$Os ratios (0.705940–0.705969) than the Laohushan granitoids.

The different rock types of the Laohushan pluton and the mafic dikes show large variations of Nd isotopic compositions. The quartz diores and tonalite have uniform weakly negative initial $\varepsilon_{Nd}$ (–1.6 to –2.9) with two-stage model ages ($T_{DM2}$) of 1302–1409 Ma. However, the dioritic enclaves have a large variation of initial $\varepsilon_{Nd}$ values ranging from –9.2 to 0.03 and show a range of one-stage model ages ($T_{DM1}$) of 1608–1549 Ma. The hornblendite has a weakly negative initial $\varepsilon_{Nd}$ value (–2.8) but a much older single-stage model age ($T_{DM1}$ = 2.74 Ga). The dolerite dikes have weak negative initial $\varepsilon_{Nd}$ values (–0.62 to –0.57) and uniform one-stage model ages ($T_{DM1}$ = 1031–1027 Ma).

**DISCUSSION**

**Petrogenesis of Dioritic Enclaves and Host Granitoids**

**Assessment of Crustal Contamination and Fractional Crystallization**

Mantle-derived magmas may be contaminated by continental crust during their emplacement. Therefore, before discussing magma sources, it is necessary to evaluate whether crustal contamination affected the Laohushan quartz diorite, dioritic enclaves, hornblendite xenoliths, and dolerite dikes. The HFSEs (e.g., Nb, Ta, Zr) are sensitive indicators of crustal contamination, because they have different concentrations in mantle-derived melts and continental rocks. The Laohushan quartz diorite, dioritic enclaves, and hornblendite xenoliths show much higher Zr/Nb ratios (14.4–59.9) than the estimated Zr/Nb ratios of the bulk continental crust (11.43) (Rudnick and Gao, 2014), whereas the Zr/Nb ratios of the dolerite dikes are much lower (8.3–9.6). Furthermore, the intermediate rocks, enclaves, and hornblendites lack inherited zircons, whereas the dolerite dikes contain older zircon grains. With the exception of one inherited zircon core from an enclave, the relatively homogeneous zircon Hf isotopic compositions suggest crustal contamination of the host granitoids and dioritic enclaves was insignificant. Therefore, crustal contamination played a negligible role in the petrogenesis of the Laohushan pluton, whereas the magma of the dolerite dikes was contaminated by crustal rocks.

In addition, fractional crystallization played an important role in the magma evolution in the Laohushan area. The tonalite samples possess high contents of Sr (365–511 ppm) and display positive Eu ($Eu/Eu^* = 1.40–1.64$) and Sr anomalies on the multi-element diagrams (Figs. 6A, 6B). Europium is compatible in plagioclase relative to the other REEs and Sr is more compatible than its neighboring REEs (e.g., Pr and Nd) in plagioclase (Bédard, 2006), suggesting a cumulation of plagioclase crystals. On the contrary, the quartz diorite and dioritic enclaves have slightly negative to insignificant Eu anomalies ($Eu/Eu^* = 0.71–0.90$, 0.65–1.01, respectively) (Fig. 6), indicating some fractionation of plagioclase. Furthermore, the quartz diorite, tonalite, and dioritic enclaves show compositional trends in SiO$_{2}$ versus Dy/Yb, SiO$_{2}$ versus La/Yb, and (Dy/Yb) versus (La/Yb)$_{n}$ diagrams, suggesting some fractionation of amphibole and plagioclase (Figs. 11A–11C). In addition, some accessory minerals like apatite and ilmenite reflect fractional crystallization, which is reflected by decreasing P$_{2}$O$_{5}$ and Fe$_{2}$O$_{3}$ with increasing SiO$_{2}$ (Fig. 12).

**Evidence for Magma Mixing**

A variety of models have been proposed to explain the petrogenesis of MMEs in granitoids: (1) accidental country rock xenoliths (Groat, 1937); (2) restites or refractory solid material left after forming the host melt (White and Chappell, 1977; Chappell et al., 1987; Chappell and White, 1991, 1992); (3) cognate fragments of cumulate minerals or earlier crystals from the host magma (Dodge and Kistler, 1990; Doinaire et al., 2005; Rodríguez et al., 2007; Niu et al., 2013; S. Chen et al., 2015, 2016b); and (4) magma mixing or mingling through the injection of mafic magmas into a felsic magma chamber (Didier, 1973; Vernon, 1984; Dorais et al., 1990; Hibbard, 1991; Barbarin, 1991; Barbarin and Didier, 1992; Chappell, 1996; Griffin et al., 2002; Kocak, 2006; Yang et al., 2004, 2006, 2007a, 2007b; Chen et al., 2009; M. Chen et al., 2016a; Chen et al., 2017).

The MMEs with xenolith and restite origins have older ages than the host rocks (Chappell et al., 1987; Vernon, 2014), which is obviously inconsistent with the similar crystallization ages (ca. 430 Ma) of dioritic enclaves and host granitoids of the Laohushan pluton. In addition, the restites generally have metamorphic microstructures or residual fabrics (Chappell et al., 1987; Chappell and White, 1991), which are not observed in the Laohushan enclaves. Thus, a xenolith or restite origin can be excluded.

MMEs with a cumogenetic cumulate origin are favored by many researchers based on the following lines of evidence: (1) cumulate textures; (2) similar crystallization ages, mineral assemblage and composition to the host granitoids; (3) linear evolutionary trends for whole-rock major and trace elements and identical isotopic compositions; and (4) the absence of compositional or textural disequilibrium (e.g., Dodge and Kistler, 1990; Doinaire et al., 2005; Niu et al., 2013; S. Chen et al., 2015, 2016b). The Laohushan dioritic enclaves have similar mineral assemblages, and partially overlapping whole-rock Sm-Nd isotope and zircon Lu-Hf isotope compositions to the host quartz diorite, which plausibly supports a cognate origin. However, the following observations question this: (1) the lack of typical cumulate textures; (2) different geochemical compositions (Table DR2; Fig. 6) between the host rocks and dioritic enclaves and their discontinuous evolutionary trends of whole-rock major elements with increasing SiO$_{2}$ on binary variation diagrams (Fig. 12); and (3) the variation in Sm-Nd isotopes of the MMEs all argue against a cumulate or restite origin, because restites produced after extraction of felsic melt should be in isotopic equilibrium with the residual melt (Collins, 1998), and cumulate MMEs would exhibit linear chemical variations (Yang et al., 2004). Combined with several lines of evidence from the field—petrography and zircon morphology—the hypothesis of magma mixing for the generation of the dioritic enclaves in the Laohushan pluton is considered the most likely, as discussed below.

**Field evidence.** The dioritic enclaves show a range of morphologies and the contact interfaces between the enclaves and the quartz diorite are irregular and gradational (Figs. 2C and 2F–2I). Together with the occurrence of some feldspar megacrysts within the enclaves (Figs. 2F–2H and 3D, 3E), we suggest that in addition (or hybridization) occurred between mafic and felsic magmas with mechanical transfer of crystals during magma mixing (Yang et al., 2007b). The fine-grained boundary between the quartz diorite and the dioritic microgranular enclaves indicates rapid cooling and quenching when a mafic magma, with relatively high temperature, was injected into a felsic magma (Figs. 2C and 2F–2I).

**Petrographic evidence.** Some acicular apatite crystals—a special morphology of apatite—were observed within quartz, plagioclase, amphibole, and biotite crystals in the dioritic enclaves (Fig. 3G). The acicular apatite suggests rapid cooling and crystallization of the enclave-forming magma (Wyllie et al., 1962, ...
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Donaire et al., 2005) and is considered as an indicator of magma mixing (Hibbard, 1991). Furthermore, the observation of disequilibrium textures, including the occurrence of anhedral and fine-grained amphibole inclusions within quartz crystals and plagioclase megacrysts rimmed by amphibole (Fig. 3E), likely resulted from dissolution of minerals formed in the host rocks when the mafic magma interacted with the felsic magma (Vernon, 1984; Bonin, 2004; Yang et al., 2004; Yang et al., 2006, 2007a, 2007b).

In addition, numerous plagioclase crystals in the dioritic enclaves typically exhibit core-mantle-rim like structures with compositional zonings characterized by increasing An values from core (An$_{42}$) to mantle (An$_{52}$) and decreasing An values from mantle to rim (An$_{21}$) (Figs. 3B, 3C). The unusual compositional zoning with a calcium-rich mantle (e.g., An$_{52}$ in Fig. 3B and An$_{as}$ in Fig. 3C) in the plagioclase cannot be simply explained as a cumulate, but most probably resulted from an involvement of mafic magma that would change the crystallization conditions. When the plagioclase was transferred into the enclave-forming magma, it would have been partially resorbed at higher temperatures. Partially resorbed plagioclase grains probably became new sites of mineral growth and were mantled by magmatic overgrowths with higher anorthite content (Barbarin, 1991; Chen et al., 2009). Subsequently, normal growth zoning with decreasing anorthite content toward the rim formed with decreasing magma temperature. Similar plagioclase textures and compositional zoning have been reported in many hybrid granitoids from the Sierra Nevada batholith, USA (Barbarin, 1991), Mesozoic rocks in the Taihang area, North China (Chen et al., 2009), and some collisional orogens like the Gangdese belt, South Tibet (Ma et al., 2017), and the Kunlun, Qingling-Dabie orogen, Central China (Dai et al., 2015).

Zircon morphology, Ti-in-zircon thermometry and Lu-Hf isotopes. As zircon is a common accessory mineral in most intermediate-felsic igneous rocks, its morphology, geochronology, and Lu-Hf isotopes are widely used to shed light on magmatic processes. High-resolution CL images show differences in zircon morphology between the quartz diorite and the dioritic enclaves (Fig. 7). Zircons from the host quartz
Figure 12. Variation diagrams of selected major oxides (wt%) versus SiO$_2$ (wt%) for the Laohushan pluton. Fields of subduction related adakites, delamination-related adakites, thick lower crust-derived adakites, and metabasaltic and eclogite experimental melts hybridized with peridotite are after Wang et al. (2006). Previously published data sources for dioritic enclaves and hornblende xenoliths are from Qian et al. (1998) and Chen et al. (2018).
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**Quartz Diorite and Tonalite**

The quartz diorites have SiO$_2$ of 57.6–62.4 wt% and are metaluminous to weakly peraluminous (A/CKN = 0.9–1.1). The tonalites have higher SiO$_2$ (67.8–67.2 wt%) and are weakly peraluminous (A/CKN = 1.0–1.03). In addition, these rocks show LILE and LREE enrichment and HFSE depletion and a marked decrease in P$_2$O$_5$ with increase of SiO$_2$ (Fig. 12).

These signatures are similar to arc magmas like I-type granitoids (Chappell and White, 1992, 2001). The arc-like geochemical characteristics of intermediate to felsic magmas can be generated by partial melting of mafic or intermediate lower crust (Turpin et al., 1990; Champion and Chappell, 1992), through fractional crystallization from mafic magma (Cawthorn and Brown, 1976; Wyborn et al., 1987) or interaction of basaltic magma with felsic continental crust (Grove and Donnelly-Nolan, 1986; Hildreth and Moorbath, 1988). The possibility of interaction of basaltic magma with crustal materials can be ruled out based on the absence of significant crustal contamination. In addition, direct fractional crystallization from a mafic magma would produce magma with high MgO, Mg#, Cr, Ni and low SiO$_2$, Na$_2$O, K$_2$O contents and relatively depleted isotopic features including positive $\varepsilon_{Ru}$ and $\varepsilon_{Nd}$ values, and low initial $\frac{^{87}Sr}{^{86}Sr}$ ratios, which are different from the enriched Hf isotopic features of the Laohushan quartz diorite. The Cr, Ni, and Hf isotopes are not constant from the coeval mafic dolerite through quartz diorite to tonalite (Figs. 9 and 10), which is inconsistent with the host intermediate and felsic magmas being directly evolved from mafic magma via closed-system fractional crystallization (Singer et al., 1992). Therefore, the quartz diorites were more likely produced by partial melting of the lower crust.

The quartz diorites have moderately positive $\varepsilon_{Ru}$ values (+3.0 to +6.2) and 942–1132 Ma (Table DR4), providing further evidence for the magma mixing process. Although the overlapping Hf isotopic characteristics of the dioritic enclaves and the host quartz diorite could be the result of the former cumulates in a cogenetic magma, experimental studies show that isotopic diffusivities in melts are greater than chemical diffusivities, therefore isotopic re-equilibrium occurs more rapidly than chemical re-equilibrium (Baker, 1989; Lesher, 1990). This may explain why the enclaves and host rocks have similar isotopic values but contrasting geochemical features.

Collectively, field relationships, petrography, zircon morphology, Ti-in-zircon thermometry, major and trace element characteristics, and Lu-Hf, Rb-Sr and Sm-Nd isotopic data presented in this study suggest that magma mixing combined with minor fractional crystallization played an important role in the petrogenesis of the quartz diorite and its dioritic enclaves in the Laohushan pluton and that heterogeneous sources were involved in this process.

**Heterogeneous Magma Sources**

Different rock types of the Laohushan pluton have different geochemical characteristics and show different systematic trends between major elements and SiO$_2$ (Fig. 12). In addition, they have a wide range of Hf and Nd isotopic compositions, which precludes simple magmatic differentiation in a closed system. Therefore, multiple magma sources are required to explain the various rocks of the Laohushan pluton.
As garnet has a high partition coefficient for HREE, whereas La and Sm are incompatible in garnet, melting of a magma source with garnet residue would result in significantly decreasing Yb and increasing Sm/Yb. The flat HREE pattern and increasing Dy/Yb, La/Yb, and (Tb/Yb)n ratios (Figs. 6A and 11), suggest that the melting depth was relatively shallow with the magma source in the spinel peridotite field.

**Dioritic Enclaves**

Most of the dioritic enclaves have relatively higher MgO (4.37–7.06 wt%), Mg# (41–56), Cr (36–340 ppm), and Ni (16–114 ppm) contents and lower SiO2 (48.30–50.72 wt%) than the bulk continental crust (SiO2 = 60.6 wt% and Mg# = 55) (Rudnick and Gao, 2003), suggesting that a mantle-derived component was involved. The enclaves show enriched LILE, LREE, and depleted HFSE (Figs. 6C, 6D), typical of the geochemical features of a metasomatized lithospheric mantle source at a subduction zone (Pearce, 1983; Pearce et al., 2000). The high Th/Yb (1.23–17.54), La/Nb (3.43–4.41) ratios and low La/Ba (0.02–0.06) ratios (Figs. 13A, 13B) in the dioritic enclaves are similar to those of magmas derived from subduction-modified lithospheric mantle (Thompson and Morrison, 1988). The low Ba/Th (29.9–61.4) (Fig. 13C) and Sr/La (10.5–13.15) ratios (Fig. 13D) indicate the involvement of sediments in their petrogenesis (Woodhead et al., 2001). In addition, the dioritic enclaves are characterized by enriched Sr and Nd isotopic compositions, with relatively high initial ⁸⁷Sr/⁸⁶Sr ratios (0.706609–0.707627), positive initial εNd (+37.3 to +90.6), variable initial εNd (−9.2 to +0.03) values, suggesting that a metasomatized lithospheric mantle with depleted Sr-Nd isotopic features could not be the single magma source. Moreover, their moderately positive zircon initial εHf (+3.0 to +5.9) values might have resulted from addition of some crustal material, which is similar with that of the granitoid rocks in the Central Asian orogenic belt produced by mixing of old crust and depleted mantle-derived material (Kröner et al., 2014, 2017). As discussed above, multiple lines of evidence suggest that magma mixing is responsible for the generation of the enclaves and little crustal contamination occurred during magmatic emplacement. Thus, crustal materials are likely to have been one of the magma sources during magma mixing.
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We modeled Sr and Nd isotopic compositions with two-end members, to evaluate the signatures of the hypothetical mantle and crustal sources involved in generating the enclaves. In this model, the lower continental crust (LCC) (Jahn et al., 1999) was selected as the crustal end-member, and the depleted mantle (DM) (Zindler et al., 1984; Zindler and Hart, 1986; Workman and Hart, 2005) was adopted as the mantle end-member. The results show that the dioritic enclaves were generated by mixing of ~93%–95% mantle-derived basaltic magma with ~7%–5% crust-derived magma (Fig. 10B). The Sm/Yb ratios of the enclaves further suggest that their parental magmas originated from a spinel-garnet lherzolite source at lower crustal depths (~45 km), with crustal pressures of ~1.2 GPa.

Hornblende Xenoliths

The hornblende xenoliths (ca. 448 Ma) have low contents of SiO₂, Na₂O, K₂O and high Mg# (74–76) values, Cr (674–747 ppm), and Ni (94–149 ppm) contents, indicating a contribution of mantle peridotite to their magma source. They have slightly enriched LREE (La/Sm = 0.91–1.39), significantly enriched Th, U, and Pb, and variably depleted Nb, Ta, and Ti (Fig. 6D), consistent with a subduction-related mantle source (Pearce, 1983, Hawkesworth et al., 1993, 1997; Plank and Langmuir, 1993; El- liott et al., 1997; Pearce et al., 2000; Chauvel et al., 2008; Dilek and Furnes, 2011; Stern, 2011). The near-flat HREE patterns (Th/Yb = 1.21–1.27) suggest a spinel peridotite source. In addition, their Sr-Nd isotopic compositions are characterized by relatively high initial ⁶⁷Sr/⁶⁳Sr ratios (0.703705), slightly negative εNd value (~2.8) and much older stage model ages (TDM = 2.74 Ga) relative to their crystallization age (ca. 448 Ma), coupled with low, mostly positive zircon initial εNd (~0.4 to +1.4) values and old one-stage Hf model ages (1008–1089 Ma), suggesting involvement of enriched crustal material. The Archean–Proterozoic whole-rock Nd and zircon Hf model ages are similar to those of the basement rocks in the Alxa terrane and the Nd-isotope-depleted oceanic crust (Qian et al., 2013) and the new-formed back-arc oceanic basin (Qian et al., 2013).

Dolerite Dikes

The dolerite dikes (ca. 427 Ma) are synchronous with the quartz diorite (ca. 426 Ma) of the Laohushan pluton, suggesting a link between the mafic dikes and the pluton. The dolerite dikes have low SiO₂ (47.6–52.8 wt%), high contents of Cr (474–528), Ni (326–367), and Mg# (71–72), indicating a mantle origin. They are characterized by extreme enrichment in LREE ((La/Yb)N = 52–76), LILE (Rb, Ba, Th, U), and depletion in HFSE (Nb, Ta, and Ti) (Figs. 6C, 6D), showing typical subduction-related geochemical characteristics. Incompatible element ratios (e.g., Ce/Y, Nb/Yb, and Th/Ta)/(Th/Tb)) can be used to distinguish different mantle sources, as Ce and La are more incompatible than Y and Yb. Hence, rocks with the smallest degree of partial melting or derived from enriched sources are expected to exhibit high Ce/Y and (La/Yb) ratios. Therefore, the high Ce/Y (9.8–13.1) and (La/Yb), (52–76) ratios of the Laohushan dolerite dikes indicate a small degree of partial melting of an asthenosphere-derived mantle source. The highly depleted HREE (Th/Yb = 2.76–3.36) and further supports garnet residue in the source, as shown in the (La/Sm), vs (Th/Yb) diagram (Figs. 6C and 11D). In addition, the dolerite dikes have high Th/Yb and low Sr/La, Ba/Th ratios (Fig. 13), probably indicating involvement of some crustal material.

The dolerite dikes have a wide range of zircon ages with many xenocrysts (442–1639 Ma). These zircons have variable initial εNd values from ~15.1 to +14.1, and can be divided into three groups. Group 1 has moderately positive initial εNd values (+3.9 to +4.8) with crystallization ages between 420 and 430 Ma, which are similar to those of the quartz diorite in the Laohushan pluton. The moderately positive initial εNd values suggest involvement of an enriched mantle in the origin of the dolerite dikes. Group 2 have high positive initial εNd values (+14.1 to +13.9) with crystallization ages of ca. 440 Ma which are similar to those of the gabbro sheet (+12.3 to +15.3) of the Laohushan ophiolite (448 Ma) (Song et al., 2013), suggesting inheritance from the gabbro sheet and interaction between the mantle-derived magma and accreted oceanic crust. Group 3 zircons have negative initial εNd values (~15.1) with crystallization ages of 449 Ma and a single-stage Hf model age (1568 Ma), consistent with contamination by upper crust. Therefore, the Hf isotopic data of the zircons from the dolerite dikes indicate that the magma was contaminated by various materials including old continental crust and accreted oceanic crust during magma emplacement, further supporting the heterogeneous nature of the lower crust of the North Qilian orogenic belt.

Geodynamic Processes and Crust-mantle Interaction during Subduction and Collision

Extensive mass and energy exchange between the mantle and the crust mainly occurs at convergent plate margins during oceanic subduction, arc/continent-continent collision, post-collision, and continental subduction stages (Tsutsumi and Egglins, 1995). Two major mechanisms for crust-mantle interaction have been proposed: (1) reaction of hydrous subduction-derived silicate melts and fluids with mantle peridotite (Z.F. Zhao et al., 2017a; Dai et al., 2017) and (2) underplating of mantle-derived magmas beneath the lower crust that may trigger partial melting of the lower crust and mixing of mantle- and crust-derived melts (Furlong and Fountain, 1986; Fyfe, 1992; Thybo and Artemieva, 2013).

Here, we recognize two episodes of crust-mantle interaction in the North Qilian orogen, which are respectively related to oceanic subduction at ca. 448 Ma and collision at ca. 430 Ma (Fig. 14). The age of the hornblende xenoliths is similar to the age of the gabbroic sheet (ca. 448 Ma) in the Laohushan ophiolite (Fig. 1C) (Song et al., 2013) that represents the formation age of oceanic crust during the opening of the North Qilian back-arc basin. The negative initial εNd (~2.8) value and old Nd model age (TDM = 2.74 Ga) of the hornblende xenoliths are different from those of the gabbroic sheet (Song et al., 2013) and accreted oceanic basalts in the North Qilian orogenic belt, suggesting different sources for these rock units. As discussed earlier, the geochemical characteristics suggest that the hornblende xenoliths were most likely derived from partial melting of the metasomatized subcontinental lithospheric mantle beneath the Archean-Proterozoic basement of the Alxa terrane (Dan et al., 2012). We infer that northward oceanic subduction beneath the Alxa terrane in the Cambrian–Ordovician resulted in ca. 490–448 Ma back-arc spreading in North Qilian and extensive metasomatization of lithospheric mantle by fluids/melts derived from oceanic crust and sediments. This process led to the formation of the Nd-isotope-enriched hornblende cumulates (ca. 448 Ma) in the subcontinental lithosphere mantle beneath the Alxa terrane and the Nd-isotope-depleted oceanic crust (εNd~N = +3.0 to +8.9, ca. 448 Ma Laohushan ophiolitic rocks in the northern ophiolite belt) derived from the depleted mantle in the newly-formed back-arc oceanic basin (Qian et al., 2001; Xia et al., 2003; Song et al., 2013). In addition, abundant coeval adakitic granitoids (ca. 460–440 Ma) were developed along the north part of the North Qilian orogenic belt.

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Gao et al. (2007) and the southern segment of the Alxa terrane (Tseng et al., 2009; Yu et al., 2015; L. Q. Zhang et al., 2017b) and the southern segment of the Alxa terrane (Liu et al., 2016), supporting a northward subduction polarity of the paleo-Qilian ocean (Tseng et al., 2009; Song et al., 2013). Continuous subduction ultimately resulted in the consumption of the oceanic crust and final collision between the Alxa terrane and the assembled Central Qilian-Qaidam blocks in the Silurian (e.g., Xia et al., 2003; Song et al., 2013). Due to buoyancy differences, slab breakoff might have taken place, as seen in many collisional orogens (e.g., Davies and von Blanckenburg, 1995, 1996) during the early collisional stage, followed by subsequent asthenospheric upwelling. During this process, asthenospheric mantle-derived magma supplied both heat and mantle material, which underplated the lower part of the accretionary prism and triggered partial melting of juvenile crustal material accompanied by crust-mantle interaction (Davies and von Blanckenburg, 1995). The formation of the Laohushan pluton (quartz diorite, tonalite with dioritic enclaves) is attributed to partial melting of lower crust dominated by accreted oceanic crust and sediments, accompanied by local magma mixing with the mantle-derived magma (Fig. 14). Moreover, the underplated mantle magma resulted in the formation of some coeval dolerite dikes. Such collision-related magmas have been documented in many accretionary-to-collisional orogenic belts worldwide, such as the Central Asian orogenic belt and Himalayan orogenic belt (e.g., Jahn et al., 2000a, 2000b; Jahn, 2004; Wu et al., 2000; Chung et al., 2005; Tang et al., 2017; Li et al., 2017).

**Multi-Episodes of Early Paleozoic Magmatism and Implications for Continental Growth**

Magmatic rocks can be generated in various stages of an orogeny and provide great insights into the relationship between the source constituents, geodynamic setting, and tectono-thermal conditions during orogenesis. They also have significant implications for understanding the interaction between asthenospheric and lithospheric mantle and continental crust (Dewey, 1988). Voluminous granitoids with distinct geochemical and isotopic characteristics have been recognized in the North Qilian accretionary belt. Importantly, they show close spatial and temporal relationships with different tectono-thermal events and geodynamic processes during the evolution of the orogen (Fig. 15).

Cambrian to Early Devonian granitic rocks (516–414 Ma) are widespread in the North Qilian accretionary belt (Fig. 1B). Combined with geochronological data discussed above and previous studies, we review the four upperplate tectono-magmatic scenarios (i.e., excluding magmatism associated with the generation of oceanic crust) recorded in the North Qilian orogenic belt (Fig. 15). The first episode of magmatism formed the 516–505 Ma Chaidanuo...
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Recent studies suggested that they formed during continent-continent collision (Yu et al., 2015; L.Q. Zhang et al., 2017b). However, the existence of the ca. 448 Ma Laohushan pluton and ca. 446 Ma Baiyin volcanic rocks clearly indicate that the development of oceanic crusts and subduction-accretionary events occurred during that time. Therefore, the second episode of adakitic magmatism could have resulted from partial melting of thickened crust induced by a northward subduction rather than by the continent-continent collision (Tseng et al., 2009). The third episode of magmatism was dominated by ca. 435-414 Ma magmatic rocks, including ca. 430 Ma Qumushan and Laohushan granitoid pluton, 427 Ma dolerite dikes, 424 Ma Jinfosi S-type granites, and ca. 427-414 Ma Wuwei-Jinchang pluton (Tseng et al., 2009; S. Chen et al., 2016b; L.Q. Zhang et al., 2017b). This generation of magmatism is widely considered to have formed during syn- and post-collisional stages due to the terminal collision between the Alxa terrane and Central Qilian-Qaidam blocks, as indicated by ca. 438-420 Ma continental deep subduction with burial depth of ~100–200 km along the North Qaidam UHP metamorphic belt (Figs. 1B and 15). In addition, some younger post-orogenic granites (ca. 403–374 Ma) were formed by melting of the upper continental crust with minor mantle-derived basaltic magmas (Chen et al., 2014), the 501 Ma Kekeli quartz diorite and the 477 Ma Niuxinshan granite, produced by subduction of the paleo-Qilian ocean (Wu et al., 2004, 2006, 2010, 2011). The second episode of plume-related magmatism is represented by ca. 457–441 Ma adakitic granitoids along the north section of the North Qilian orogenic belt, including ca. 457–446 Ma Xigela-Quwushan pluton, ca. 453 Ma Leigongshan pluton, and 443–441 Ma Mengjiadawan-Lianhuashan pluton (Tseng et al., 2009; Yu et al., 2015; L.Q. Zhang et al., 2017b). Some recent studies suggested that they formed during continent-continent collision (Yu et al., 2015; L.Q. Zhang et al., 2017b). However, the existence of the ca. 448 Ma Laohushan pluton and ca. 446 Ma Baiyin volcanic rocks clearly indicate that the development of oceanic crusts and subduction-accretionary events occurred during that time. Therefore, the second episode of adakitic magmatism could have resulted from partial melting of thickened crust induced by a northward subduction rather than by the continent-continent collision (Tseng et al., 2009). 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recognized in the north part of the North Qilian orogenic belt (Wu et al., 2004, 2010; Song et al., 2013).

The growth of continental crust occurs mainly through two major mechanisms in the Phanerozoic: lateral accretion of arcs and accretionary complexes at subduction zones or by vertical addition of mafic magmas underplating the crust-mantle interface (Rudnick, 1990, 1995; Şengör et al., 1993; Hawkesworth et al., 1993; Frost et al., 2001; Kemp and Hawkesworth, 2003). Continental crustal growth has long been attributed to island arc magmatism, mainly occurring during accretionary orogenic processes (McCulloch and Bennett, 1994; Polat and Kerring, 2000). Recent studies on syn-collisional granitoids in continental collision zones (e.g., Mo et al., 2008) suggest that continental collision zones may also be primary sites of net continental crust growth (Kröner et al., 2014, 2017). Decoupling of the Sm-Nd and Lu-Hf isotopic systems was evident in our study, and previous studies suggested that the Sm-Nd system is more prone to disturbance by metamorphism and/or alteration (e.g., Black and McCulloch, 1987; Poitrasson et al., 1995; Vervoort and Blichert-Toft, 1999), because Nd is more mobile than Hf in aqueous fluids (Thompson et al., 2008). In contrast, zircon can resist high-grade metamorphism, and it has low Lu/Hf ratios that can preserve the initial $^{176}$Hf/$^{177}$Hf of the source magma during crystallization. Thus, the Lu-Hf isotopic system can effectively preserve the initial $^{176}$Hf/$^{177}$Hf of the source magma (Polat and Münker, 2004). Our systematic Hf isotopic investigation of early Paleozoic multiple episodes of magmatism in the North Qilian accretionary belt suggests a wide range of zircon initial $\epsilon_{Hf}$ values from depleted to slightly enriched mantle sources (Fig. 9), indicating the contributions of mantle-derived magmas and juvenile material. In North Qilian, such addition of mantle material to the continental crust was mainly through vertical growth by magma underplating during collisional and post-collisional events at ca. 430–420 Ma. During the Late Ordovician to Early Silurian (ca. 448 Ma), North Qilian oceanic crust formed in a back-arc basin and was subducted. The input of mantle magma, related to subduction, may represent lateral growth owing to the amalgamation of the Alxa terrane and Central Qilian-Qaidam blocks. Therefore, the multiple episodes of early Paleozoic magmatism led to significant crustal growth.

Through various processes, including large-scale post-collisional magmatism, high-grade metamorphism or delamination, the orogenic crust can be significantly strengthened and stabilized and subsequently converted to mature continental crust. Among these processes, the generation of large granitoid batholiths would change the density and thermal conductivity properties of the lithosphere and remove any mechanical weaknesses (Kusky, 1993). Therefore, the generation of collision-related magmas after accretionary processes plays an important role in the stabilization of the crustal structure of orogenic belts.

The production of the type of collision-related magmatism documented in this study mainly involves asthenospheric upwelling, mafic magmatic underplating, and reworking of the juvenile lower crust. On the one hand, the underplating magma would melt the newly-accreted materials, prompting the anisotropic lower crust to be transformed into relatively homogeneous compositions and welded together (Harris et al., 1996; Holister and Andronicos, 2006; Scharman et al., 2012). In addition, underplating may also add high-density material to the deep crust. This is because the extraction/magma fractionation of the granitic melt can leave a high-density garnet-and/or garnet-pyroxene granulite residue in the deep crust. Therefore, we suggest that the lower crust beneath the Qilian orogenic belt gradually became cooler and denser after production of the collision-related magma. Following the separation of the low-density material from the high-density residue, the crustal structure was strengthened and matured, a process akin to cratonization (e.g., Kusky and Polat, 1999).

CONCLUSIONS

The Early Silurian (ca. 430 Ma) collision-related Laohushan pluton intruded an accretionary complex developed along the eastern margin of the North Qilian accretionary belt. The pluton mainly consists of ca. 426 Ma quartz diorite with ca. 430 Ma dioritic microgranular enclaves and ca. 450 Ma hornblende xenoliths. The quartz diorite was most likely produced by partial melting of accreted juvenile lower crust, consisting of basalts and sedimentary rocks. The dioritic enclaves were likely formed by magma mixing of mantle-derived magmas and crust-derived melts, as indicated by field observations, petrographic studies, and geochemical analyses. The hornblende xenoliths originated from partial melting of the subcontinental lithosphere mantle peridotite beneath the Alxa terrane. Whole-rock Rh-Sr and Sm-Nd and zircon Lu-Hf isotopic data indicate significant vertical continental growth during the collisional orogenesis in Qilian Shan, northeastern Tibet. We highlight the contribution of previously-accreted lithologies formed during accretionary orogenesis in the genesis of these rocks.

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REFERENCES CITED

Collision-related magmatism in North Qilian orogen


Chappell, B.W., 1996. Magma Mixing and the Production of Compositiona...


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