Petrogenesis of Early Paleozoic high Sr/Y intrusive rocks from the North Qilian orogen: Implication for diachronous continental collision

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ABSTRACT

A combination of U-Pb zircon ages and geochemical and Sr-Nd-Hf isotopic data are presented for the Early Paleozoic granodiorites from the Haoquangou and Baimawa plutons in order to probe the crustal thickness variation of the eastern North Qilian and the diachronous evolution of the North Qilian orogen. The granodiorites formed at 436–435 Ma and have high Sr/Y ratios (63–117). Elemental and isotopic data combined with geochemical modeling and comparisons with experimental data suggest that they were produced from the melting of relatively juvenile mafic rocks in the thickened lower crust. Together with other petrological and geochemical data and the calculation of variation in crustal thickness, this indicates that the eastern North Qilian experienced clear crustal thickening and thinning from the Late Ordovician to Late Silurian. Based on available data, we suggest that diachronous collision from east to west, which probably resulted in the distinct intensity of orogenesis between eastern and western North Qilian, can well account for the differential distribution of Early Paleozoic high Sr/Y magmatism and other geological differences between the eastern and western parts of the North Qilian. Our study also implies that diachronous collision may lead to, apart from distinct metamorphic, structural and sedimentary responses, the large differences in magmatism and deep crustal processes along the orogenic strike.

INTRODUCTION

Magmatism is abundant in continental orogenic belts and it well records thermal evolution of lithosphere (Wilson, 1989). Its genesis and temporal-spatial distribution can provide important insights into the tectonic evolution and deep geodynamic processes of orogenic belts, such as diachronous collision or post-collision processes (Richards, 2015; Hu et al., 2016). High Sr/Y (or adakitic) rocks, as a special type of magmatic rocks, have been widely studied in terms of their petrogenesis and tectonic settings, their relationship with Cu-Au metasomatism, and their implications for the growth of early continental crust (Defant and Drummond, 1990; Martin et al., 2005; Wang et al., 2006b; Moyen, 2009; Schwartz et al., 2011; Castillo, 2012). High Sr/Y rocks are characterized by low HREE contents and high Sr/Y (> 40) and La/Yb ratios, suggesting that they were generated at pressures high enough to stabilize garnet and/or amphibole (Defant and Drummond, 1990; Castillo, 2012). High Sr/Y rocks were originally considered to be products of young (< 25 Ma) slab melting in arc settings (Defant and Drummond, 1990), but later studies suggested that high Sr/Y rocks can also be produced through other petrogenetic processes in both arc or non-arc settings (Atherton and Petford, 1993; Castillo et al., 1999; Chung et al., 2003; Martin et al., 2005; Macpherson et al., 2006). In particular, many high Sr/Y rocks were inferred to be derived from the continental lower crust (Atherton and Petford, 1993; Chung et al., 2003; Wang et al., 2006b; Yu et al., 2019b), but whether crustal thickening is necessary for their formation is still controversial. For example, while many high Sr/Y rocks were suggested to result from deep melting of basaltic sources at pressures equivalent to a crustal thickness of >40–50 km and crustal thickening was thought to be needed for their generation (Atherton and Petford, 1993; Rapp and Watson, 1995; Chung et al., 2003; Wang et al., 2006b), some researchers have argued that, based on recent studies on experimental petrology and geochemical modeling, high Sr/Y rocks can form from crustal melting at pressures as low as 1.0 GPa and the overthickened crust may not be necessary (Moyen, 2009; Qian and Hermann, 2013; Ma et al., 2015). Even so, the occurrence of widespread continental high Sr/Y granitoids is often regarded as a sign of a collision or post-collision process (Chung et al., 2003; Schwartz et al., 2011; Yu et al., 2019a). Moreover, Sr/Y and La/Yb ratios in intermediate magmatic rocks have been used to quantify crustal thickness over time in magmatic arcs or continental collisional belts (Chapman et al., 2015; Profeta et al., 2015; Hu et al., 2017; DePaolo et al., 2019). Thus, whether high Sr/Y granitoids can indicate crustal thickening, which is important for the understanding of orogenic evolution, needs further evaluation.

Early Paleozoic high Sr/Y plutons are widely distributed in the eastern part of the North Qilian belt and many are genetically associated with Cu-Au deposits (Wang et al., 2006a; Tseng et al., 2009; Chen et al., 2016; Zhang et al.,...
mainly formed in the Late Neoproterozoic to Middle Neoproterozoic (Wan et al., 2001; Yan et al., 2015), corresponding to assembly and breakup of the Rodinia supercontinent. This, combined with Pb-Nd isotopic data, suggests that the Central Qilian block has an affinity with the Yangtze block (Wan et al., 2001; Zhang et al., 2006). Early Paleozoic intrusive rocks are abundant in the Central Qilian, dominated by granitic rocks (including high Sr/Y, I-, S- and transitional I-S type granitic rocks), with less diorites and mafic-ultramafic intrusive rocks (Yang et al., 2018, and references therein) (Fig. 1B). They commonly intrude the Precambrian basements. These intrusive rocks, less exposed volcanic rocks, and related metamorphic rocks in the Central Qilian were suggested to be the products of subduction of the South Qilian oceanic slab and subsequent continental collision and post-collision processes during the Early Paleozoic period (Bian et al., 2001; Xia et al., 2016; Li et al., 2018).

GEOLOGICAL BACKGROUND

The Qilian orogen, located in the northeastern margin of the Tibetan Plateau, is a NWW-trending linear belt lying between the Alax block and the North Qaidam–West Qinling belts (Figs. 1A and 1B). It is separated from the Ordos block to the east and the Tarim Craton to the west by the Tongxin-Guyuan fault and the Ailty Tagh fault, respectively (Feng and He, 1996). It formed by Early Paleozoic convergence of the Alax, Central Qilian, and Qaidam blocks (Yang et al., 2012; Song et al., 2013; Xia et al., 2016). Tectonically, the Qilian orogen can be divided into three units from south to north: South Qilian belt, Central Qilian block, and North Qilian belt (Fig. 1B).

The South Qilian mainly comprises Cambrian–Ordovician volcanic-sedimentary rocks (lava flows, pyroclastic rocks, and abyssal and bathyal deposits), Silurian flysch sediments, Late Devonian molasses, and Late Caledonian granitoids (Xu et al., 2006) (Fig. 1B). The Cambrian–Ordovician volcanic-sedimentary strata are mainly distributed in the northern part of the South Qilian. Geochemical data indicate that the Ordovician volcanic rocks were probably generated in a subduction setting (Zhao et al., 2004). Early Paleozoic granitoids are widespread in the South Qilian and commonly occur as batholiths or stocks. Geochronological data suggest that they mainly formed at 473–433 Ma (Wu et al., 2006; Wang et al., 2013), probably recording oceanic subduction and closure of the South Qilian Ocean.

The Central Qilian block mainly comprises Precambrian metamorphic basements, Early Paleozoic magmatic rocks (especially intrusive rocks), and Paleozoic to Mesozoic sedimentary strata (Feng and He, 1996) (Fig. 1B). Geochronological data imply that the Precambrian basement rocks in the Central Qilian were suggested to be the products of the cold subduction and later exhumation of the North Qilian oceanic slab (Zhang et al., 2007; Song et al., 2009). The eclogite-facies rocks have U-Pb zircon ages of 489–463 Ma (Song et al., 2004; Zhang et al., 2007), and blueschist-facies rocks have 40Ar-39Ar ages of ~460–410 Ma (Zhang et al., 1997; Liu et al., 2006). Late Ordovician–Silurian magmatic rocks, including high Sr/Y, I- and A-type granitoids, have been identified in the North Qilian and their magma generation was linked to late-stage oceanic subduction, continental collision, or post-collision processes (Chen et al., 2012; Zhao et al., 2014; Yu et al., 2015; Zhang et al., 2017b).

There are many Early Paleozoic granitic plutons (e.g., Haqoungou, Baimawa, Heishishangou, and Fangfuyaa plutons) in the Heishishan area of the eastern North Qilian (Fig. 2) that are closely related to regional Cu-Au mineralization (Wang et al., 2005b). These small intrusions occur as stocks, apophyses, and dykes, and intrude Cambrian–Ordovician arc volcanic rocks. The dominant rock types are granodiorite and trondhjemite (Wang et al., 2005b). The granodiorite samples used in this study were collected from the Haqoungou and Baimawa plutons (Figs. 2, 3A, and 3B). The Haqoungou pluton is located ~3 km north of the Baiyin City, with an outcrop area of ~0.03 km² (Figs. 1B and 2). It hosts Au deposits and comprises medium-grained and undeformed rocks, ranging in composition from trondhjemite to granodiorite (Wang et al., 2005b). Some small granite-porphyry dykes associated with the Haqoungou pluton have also been reported (Wang et al., 2005b). The Baimawa pluton lies ~1 km northeast of the Haqoungou pluton and has an outcrop area of ~0.24 km² (Fig. 2). It mainly consists of medium-grained granodiorite. The granodiorites from the Haqoungou and Baimawa plutons are mainly composed of quartz (~20–25 vol.%), plagioclase (~50–55 vol.%), K-feldspar (~10 vol.%), biotite (~10–15 vol.%), and secondary muscovite that most likely resulted from decomposition of plagioclase or transformation from other minerals such as biotite (Figs. 3C–3F). Polysynthetic twinning and zonal structure in the plagioclase and garnet and Carlsbad twinning in the K-feldspar have been observed. Zircon, apatite, and Fe-Ti oxides are common accessory minerals.

ANALYTICAL METHODS

Fresh rock samples were crushed to powders of 200 mesh in an agate mill. Major element compositions were determined by X-ray fluorescence (XRF) at the State Key Laboratory of Geological Processes and Mineral Resources (GPMR), China University of Geosciences, Wuhan. The detailed procedures for XRF...
Figure 1. (A) Geological sketch map showing the major tectonic units of China (modified from Yang et al., 2009). (B) Simplified geological map of the Qilian orogen, showing distribution of the Precambrian basement and the Early Paleozoic rocks (modified after Ma et al., 2002). Data sources for zircon U-Pb ages in B are as follows: Leigongshan (LGS) tonalite and Shenmutou (SMT) quartz monzonite—Tseng et al. (2009); Quwushan (QWS) granodiorite and granite—Yu et al. (2015), Chen et al. (2016); Xigela (XGL) granite—Yu et al. (2015); Maozangsi (MZS) granodiorites—Xiong et al. (2012), Yu et al. (2015); Laohushan (LHS) quartz diorite—Qian et al. (1998); Jingzichuan (JZC) quartz diorite—Wu et al. (2004); Baojishan (BJS) granodiorite—Chen et al. (2015); Mengjiaadawan (MJDW) granodiorite and quartz diorite, Lianhuashan (LHSH) granodiorite, Yangqiandashan (YQDS) granodiorite, Shenrongsi (SRS) alkali-feldspar granite and Xinkaigou (XKG) porphyritic and fine-grained granites—Zhang et al. (2017b); Minyueyaogou (MYYG) granodiorite and Niuxinshan (NXS) quartz diorite—Zhang et al. (2017b); Kekeli (KKL) plagiogranite—Wu et al. (2010); Chaidanuo (CDN) granite—Chen et al. (2014); Jinfosi (JFS) dioritic-granitic rocks—Wu et al. (2010), Huang et al. (2017); Aoyougu (AVG) trondhjemite—Chen et al. (2012); Xiaoliugou monzogranite and granodiorite—Zhao et al. (2014); Jingteishan (JTS) granite—Li et al. (2019); Yeniutan (YNT) granite—Mao et al. (2000); Changmaxi (CMX) granite—Gehrels et al. (2003). The eastern North Qilian is roughly separated from the western North Qilian by the dashed line shown in B, for convenience of discussion on the diachronous evolution in this study.
Figure 2. Geological map of the Haoquangou and Baimawa plutons in the eastern North Qilian.

Figure 3. Field photographs of the (A) Haoquangou pluton and (B) Baimawa pluton. Cross-polarized light photomicrographs of representative samples from the Haoquangou and Baimawa plutons: (C–D) Haoquangou granodiorite (Q1211), and (E–F) Baimawa granodiorite (Q1214 and Q1215). Mineral abbreviations (Whitney and Evans, 2010): Qz—quartz; Pl—plagioclase; Kfs—K-feldspar; Bt—biotite; Ms—muscovite.
analyses are the same as those described by Ma et al. (2012). Data quality was monitored by simultaneous analyses of repeated samples (one in ten samples) and the standard samples GBW07104 (GSA Data Repository Table DR11), and analytical uncertainties were generally less than 5%.

Whole-rock trace elements (including rare earth elements) were analyzed by ICP-MS at GPMR. For the detailed procedures for ICP-MS analyses, see the description by Liu et al. (2008). During analysis, compositions of USGS reference materials AGV-2, BHVO-2, BCR-2, GSP-2, and RGM-1 were also measured to monitor data quality (Data Repository Table DR2). Analytical uncertainties were less than 5% for most trace elements.

Whole-rock Sr-Nd isotopic compositions were acquired using a Triton thermal ionization mass spectrometer at GPMR. Details for Sr-Nd isotopic analyses are similar to those described by Zhang et al. (2017a). Measured Sr and Nd isotopic ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{144}\text{Nd}/^{142}\text{Nd} = 0.7219$, respectively, for mass fractionation corrections. During the analyses, the NBS987 standard yielded an average $^{86}\text{Sr}/^{88}\text{Sr}$ value of $0.710239 \pm 0.000010$ (2σ) and the BCR-2 standard gave an average $^{143}\text{Nd}/^{144}\text{Nd}$ value of $0.512620 \pm 0.000012$ (2σ); these were identical within error to the previously reported values (Thirlwall, 1991; Weis et al., 2006).

Zircons were separated from whole-rock samples by conventional heavy liquid and magnetic techniques, and then were selected under a binocular microscope. The selected zircon grains were mounted in epoxy resin and then polished to about half of their thickness. Transmitted and reflected light photomicrographs and cathodoluminescence (CL) images were taken to reveal the morphology and internal texture of zircons and guide the selection of in situ analysis spots. CL imaging was carried out at the State Key Laboratory of Continental Dynamics, Northwest University, Xi’an, China. Zircon U-Pb dating and trace element analyses were conducted using LA-ICP-MS at GPMR. The detailed analytical procedures are the same as described by Liu et al. (2010). Spot sizes adopted in this study were 32 μm. Zircon standard 91500 and NIST SRM610 glass were used as external standards for the calibration of Pb/U ratios and concentrations, respectively. Offline selection and integration of background analyte signals and time-drift correction and quantitative calibration were performed using ICPMSDataCal (Liu et al., 2010). Data correction and processing followed methods similar to those in Yang et al. (2015). Zircon standard GI-1 was used as a reference standard. During the analyses, it gave a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of $608 \pm 5$ Ma (n = 7, MSWD = 0.73), and $0.282679 \pm 11$ (n = 4, MSWD = 1.1), respectively (Data Repository Table DR4), which agree with the recommended reported values within error (Woodhead et al., 2004; Eilhhoul et al., 2006). Calculations of $\epsilon_{400}(t)$ values and Hf model ages ($T_{\text{chondri}}$,t) were similar to those in Yang et al. (2015).

RESULTS

Zircon U-Pb Geochronology

In this study, sample Q1211 from the Haoquangou pluton and sample Q1214 from the Baimawa pluton were selected for zircon U-Pb dating. Zircons from samples Q1211 and Q1214 are mostly euhedral to subhedral. They show long to short prismatic crystals, 70–200 μm in length and length-to-width ratios of 2:1–4:1. In CL images, they display weak oscillatory zoning (Figs. 4A and 4B). Fifteen zircon analyses were obtained from sample Q1211 (Data Repository Table DR5), with U of 629–1231...
ppm and Th of 310–564 ppm, and Th/U ratios of 0.37–0.59. All the analyses are concordant or nearly concordant and yield a weighted mean \(^{206}\text{Pb}/^{238}\text{U}\) age of 436 ± 2 Ma (MSWD = 1.07) (Fig. 4A), which is interpreted as the magma crystallization age of the Haoquangou pluton. Fourteen zircon analyses from sample Q1214 display U and Th contents ranging from 666 to 1212 ppm and 292–654 ppm, respectively, with relatively uniform Th/U ratios of 0.41–0.54 (Data Repository Table DR5). They yield a weighted mean \(^{206}\text{Pb}/^{238}\text{U}\) age of 435 ± 2 Ma (MSWD = 1.13) (Fig. 4B), representing the crystallization age of the Baimawa pluton.

### Major and Trace Elements

The granodiorites from the Haoquangou and Baimawa plutons share similar geochemical characteristics (Table 1). They are also similar to the Haoquangou granodiorite-trondhjemites and associated granite-porphyries reported by Wang et al. (2005b) in chemical composition (Figs. 5A–5D). The granodiorites in this study are subalkaline and characterized by high SiO\(_2\) (68.12–70.10 wt%) and CaO (2.07–3.51 wt%) and low MgO (0.95–1.17 wt%) contents (Fig. 5B), with Mg# of 46–49 (Table 1). They plot in the granodiorite field in the total alkalis versus SiO\(_2\) classification diagram (Fig. 5A).

### Table 1. Major Element and Trace Element Data

| Sample        | Pluton | Rock type | Q1210 | Q1211 | Q1213 | Q1214 | Q1215 | Q1216 | Q1217 | Q1218 | HQG* |
|---------------|--------|-----------|-------|-------|-------|-------|-------|-------|-------|-------|------|
|               |        |           | GD    | GD    | GD    | GD    | GD    | GD    | GD    | GD    | TR+GD+GP |
| **Major elements (wt.%)** |       |           |       |       |       |       |       |       |       |       |      |
| SiO\(_2\)     | 69.37  | 69.19     | 70.10 | 68.12 | 69.25 | 68.67 | 69.49 | 68.97 | 69.32 | 72.38 |
| TiO\(_2\)     | 0.26   | 0.28      | 0.27  | 0.30  | 0.29  | 0.29  | 0.29  | 0.27  | 0.20  | 0.32  |
| Al\(_2\)O\(_3\) | 14.99  | 15.27     | 14.55 | 15.76 | 15.55 | 15.61 | 15.21 | 15.75 | 14.71 | 15.78 |
| FeO\(_T\)     | 2.18   | 2.28      | 2.29  | 2.41  | 2.35  | 2.13  | 2.47  | 2.18  | 1.90  | 2.67  |
| MnO           | 0.03   | 0.04      | 0.03  | 0.04  | 0.04  | 0.04  | 0.04  | 0.04  | 0.03  | 0.04  |
| MgO           | 0.99   | 1.03      | 1.04  | 1.06  | 1.04  | 1.03  | 1.17  | 0.95  | 0.77  | 1.31  |
| CaO           | 2.54   | 2.66      | 2.41  | 3.51  | 3.25  | 2.87  | 2.07  | 2.54  | 2.94  | 3.40  |
| Na\(_2\)O     | 0.40   | 1.48      | 3.85  | 4.09  | 4.15  | 4.47  | 3.85  | 4.29  | 4.17  | 4.50  |
| K\(_2\)O      | 2.16   | 2.13      | 2.05  | 1.71  | 2.02  | 1.79  | 2.65  | 2.17  | 1.70  | 2.16  |
| P\(_2\)O\(_5\) | 0.09   | 0.09      | 0.09  | 0.10  | 0.09  | 0.08  | 0.09  | 0.08  | 0.07  | 0.10  |
| LOI           | 2.53   | 0.74      | 2.72  | 1.85  | 1.14  | 1.64  | 2.09  | 1.93  | 0.81  | 1.58  |
| A/CNK         | 1.11   | 1.09      | 1.12  | 1.05  | 1.04  | 1.17  | 1.17  | 1.13  | 1.02  | 1.08  |
| Mg\(^{#}\)    | 47     | 47        | 47    | 47    | 47    | 49    | 48    | 46    | 45    | 50    |
| K\(_2\)O/Na\(_2\)O | 0.54   | 0.51      | 0.53  | 0.42  | 0.49  | 0.49  | 0.69  | 0.49  | 0.38  | 0.51  |

| **Trace elements (ppm)** |       |
| Cr             | 3.33   |
| Co             | 80.4   |
| Ni             | 3.96   |
| Rb             | 68.9   |
| Sr             | 369    |
| Y              | 4.29   |
| Zr             | 91.9   |
| Nb             | 5.39   |
| Cs             | 2.23   |
| La             | 14.7   |
| Ce             | 25.6   |
| Pr             | 2.58   |
| Nd             | 8.63   |
| Sm             | 1.58   |
| Eu             | 0.46   |
| Gd             | 1.14   |
| Tb             | 0.16   |
| Dy             | 0.76   |
| Ho             | 0.15   |
| Er             | 0.36   |
| Tm             | 0.061  |
| Yb             | 0.37   |
| Lu             | 0.050  |
| Hf             | 2.38   |
| Ta             | 0.62   |
| Tb             | 12.9   |
| Th             | 7.53   |
| U              | 2.18   |
| Sr/Y           | 86     |
| Eu/Eu*         | 1.01   |
| (La/Yb)*       | 28.69  |

Note: FeO\(_T\) = All Fe calculated as FeO; Mg# = \([100\text{MgO}/(\text{MgO}+\text{FeO}^\text{total})]\) (FeO\(^\text{total}\) = 0.8998 * FeO\(_T\)); HQG—Haoquangou pluton; BMW—Baimawa pluton; GD—Granodiorite; TR—Trondhjemite; GP—Granite-porphyr.

*Data from Wang et al. (2005b).*
samples possess high Na₂O (3.85–4.47 wt%) and low K₂O (1.71–2.65 wt%) contents and low K₂O/Na₂O ratios (0.40–0.69) (Figs. 5C and 5D), and belong to a high-K calc-alkaline series (Fig. 5D). These rocks show a limited variation of Al₂O₃ contents (14.55–15.76 wt%), with relatively variable A/CNK values [molar Al₂O₃/(CaO + Na₂O + K₂O)] ranging from 1.04 to 1.17. Therefore, these granodiorites exhibit peraluminous characteristics.

The granodiorite samples have low Cr (3.01–3.97 ppm) and Ni (3.27–4.35 ppm) contents. Their Sr contents range from 343 to 536 ppm and Y contents from 4.29 to 5.88 ppm, resulting in high Sr/Y ratios (63–117). In the primitive mantle-normalized trace element patterns (Fig. 6A), they show obvious enrichment of U, K, Pb, and Sr and depletion of Nb, Ta, P, and Ti, with slightly positive Zr-Hf anomalies. They have strongly fractionated REE patterns [(La/Yb)ₚ = 27.66–39.94] (Fig. 6B), with weak negative to weak positive Eu anomalies (Eu/Eu* = 0.94–1.10).

Sr-Nd-Hf Isotopes

The Haoquangou granodiorites have Iₑ values of 0.7052–0.7054 and εₑNd(t) values of −1.3 to +0.7, with depleted mantle Nd model ages [TₑNd(Nd)] of 1.02–1.23 Ga (Table 2). Zircons from sample Q1211 show relatively uniform Hf isotopic compositions, with ¹⁹⁷Hf/¹⁷⁷Hf ratios ranging from 0.282674 to 0.282750, εₑHf(t) values from +5.9 to +8.5, and depleted mantle Hf model ages [TₑHf(Hf)] from 0.71 to 0.82 Ga (Fig. 7; Data Repository Table DR6).

The Baimawa granodiorites show Sr-Nd isotopic compositions (Iₑ = 0.7051–0.7058, εₑNd(t) = +0.5 to +1.1, TₑNd(Nd) = 0.93–1.00 Ga) similar to those of the Haoquangou granodiorites (Table 2). Zircons from sample Q1214 give ¹⁹⁷Hf/¹⁷⁷Hf ratios of 0.282693–0.282751, with calculated εₑHf(t) values of +6.5 to +8.5 and TₑHf(Hf) of 0.71–0.79 Ga (Fig. 7; Data Repository Table DR6), which are also similar to those of the zircons from Haoquangou granodiorite sample Q1211.

DISCUSSION

Petrogenesis

Magmatic Processes and Magma Source

The Haoquangou granitic rocks (including the granodiorites in this study and the granodiorite-trondhjemites and associated granite-porphyries reported by Wang et al., 2005b) and the Baimawa granodiorites are all characterized by high Sr (343–540 ppm) and LREE (e.g., La = 14.7–23.7 ppm) and low
Table 2. Whole-rock Sr-Nd isotopic data

| Sample                      | $^{87}\text{Rb}/^{86}\text{Sr}$ | $^{87}\text{Sr}/^{86}\text{Sr}$ | $\pm 2\sigma$ | $^{147}\text{Sm}/^{144}\text{Nd}$ | $^{143}\text{Nd}/^{144}\text{Nd}$ | $\pm 2\sigma$ | $\epsilon_{\text{Nd}}(t)$ | $T_{\text{DM(Nd)}}$ (Ga) |
|-----------------------------|----------------------------------|----------------------------------|--------------|----------------------------------|------------------|--------------|----------------|--------------------------|
| Haoquangou pluton ($t = 436$ Ma) | 0.541                            | 0.708535                         | 4            | 0.7052                           | 0.111            | 0.512326     | 11             | -1.3                     | 1.23                     |
| Q1211                       | 0.434                            | 0.708085                         | 4            | 0.7054                           | 0.105            |              |                |                          |                          |
| Q1213                       | 0.539                            | 0.708676                         | 5            | 0.7053                           | 0.101            | 0.512399     | 11             | 0.7                       | 1.02                     |
| Baimawa pluton ($t = 435$ Ma) | 0.313                            | 0.707025                         | 5            | 0.7051                           | 0.103            |              |                |                          |                          |
| Q1214                       | 0.289                            | 0.707331                         | 6            | 0.7055                           | 0.096            | 0.512376     | 11             | 0.5                       | 1.00                     |
| Q1216                       | 0.658                            | 0.708854                         | 6            | 0.7058                           | 0.088            | 0.512385     | 13             | 1.1                       | 0.93                     |

Note: $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{147}\text{Sm}/^{144}\text{Nd}$ ratios are calculated from Rb, Sr, Sm and Nd contents, measured by ICP-MS (Table 1); $\epsilon_{\text{Nd}}(t)$ values are calculated based on present-day ($^{147}\text{Sm}/^{144}\text{Nd})_{\text{CHUR}} = 0.1967$ and ($^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}} = 0.512638$; $T_{\text{DM(Nd)}}$ values are calculated based on present-day ($^{147}\text{Sm}/^{144}\text{Nd})_{\text{DM}} = 0.2137$ and ($^{143}\text{Nd}/^{144}\text{Nd})_{\text{DM}} = 0.51315$.

Figure 6. (A) Primitive mantle-normalized trace element spider diagrams and (B) chondrite-normalized REE patterns. Chondrite and primitive mantle-normalized values are from Sun and McDonough (1989). For comparison, fields of thickened lower crust-derived high Sr/Y rocks from the North Qaidam and high Sr/Y rocks from other areas of the eastern North Qilian are also shown. Data sources: North Qaidam—Yu et al. (2012, 2019a, 2019b); eastern North Qilian—Wang et al. (2005b, 2006a, 2008), Tseng et al. (2009), Li (2012), Chen et al. (2015, 2016), Yu et al. (2015), and Zhang et al. (2017b).

Figure 7. Plots of $\epsilon_{\text{Hf}}(t)$ versus zircon U-Pb ages for the studied samples. CHUR—chondritic uniform reservoir; DM—depleted mantle. Data sources: high Sr/Y rocks—Yang et al. (2015), Yu et al. (2015), Zhang et al. (2017b), Li et al. (2019); I-type granites—Zhao et al. (2014), Zhang et al. (2017b); transitional I-S type granites—Chen et al. (2014); A-type granites—Zhang et al. (2017b).
Y (4.29–6.69 ppm) and Yb (0.32–0.58 ppm) contents, with high Sr/Y and La/Yb ratios, similar to those of adakite and Archean high-Al TTG (Figs. 8A and 8B) (Martin, 1986; Defant and Drummond, 1990). High Sr/Y rocks can be produced by the following mechanisms: partial melting of subducted oceanic slab (Defant and Drummond, 1990) or mantle peridotites that were metasomatized by slab melts (Martin et al., 2005), partial melting of continental lower crust (Atherton and Petford, 1993; Wang et al., 2006b), fractional crystallization of basaltic magmas with or without crustal assimilation (Castillo et al., 1999; Macpherson et al., 2006), or mixing of mantle-derived mafic and crust-derived felsic magmas (Chen et al., 2013).

Based on geochemical modeling, Moyen (2009) suggested that the melting of metasedimentary rocks (pelites or greywackes) can produce high Sr/Y melts. Although the Haoquangou and Baimawa high Sr/Y rocks contain (secondary) muscovite as Al-rich mineral and the four of them have A/CNK [Molar Al₂O₃/(CaO + Na₂O + K₂O)] > 1.1, they cannot be explained as S-type granites generated by anatexis of metasedimentary rocks (Chappell and White, 1974). First, they have much more depleted Sr–Nd isotopic compositions than the typical Early Paleozoic S-type rocks in the North Qilian (Fig. 9A). Second, as depicted in Figures 10A–10D, their chemical compositions are different from those of experimental melts obtained from partial melting of greywacke and pelitic sources. The transitional I–S type and A-type granites that were interpreted to be dominantly derived from felsic crustal materials have also been identified in the North Qilian (Chen et al., 2014; Zhang et al., 2017b). However, the Haoquangou and Baimawa high Sr/Y rocks differ significantly from those in their Sr-Nd-Hf isotopic compositions (Figs. 7 and 9A). Therefore, the metasedimentary rocks and felsic materials in the continental crust are not suitable sources for the generation of the high Sr/Y rocks in this study.

The Haoquangou and Baimawa high Sr/Y rocks have higher SiO₂ contents and lower Mg#, Cr, and Ni contents (Table 1) than the low-SiO₂ high Sr/Y rocks (Martin et al., 2005), which does not support their derivation by partial melting of peridotitic mantle modified by slab-derived melts. The major elements and Sr–Hf isotopic compositions of the Haoquangou and Baimawa high Sr/Y rocks all fall within a small

![Figure 8](https://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/doi/10.1130/L1129.1/4907609/11129.pdf)

Figure 8. (A) Sr/Y versus Y diagram; (B) (La/Yb)_N versus Yb_N diagram; (C–D) Cr and Ni versus SiO₂ diagrams. In A and B, fields of adakite and arc rocks are from Martin (1986) and Drummond and Defant (1990). Data sources: eastern segment—Qian et al. (1998), Wu et al. (2004), Wang et al. (2005b, 2006a, 2008), Tseng et al. (2009), Li (2012), Xiong et al. (2012), Chen et al. (2015, 2016), Yu et al. (2015), Zhang et al. (2017b); western segment—Mao et al. (2000), Chen (2009), Wu et al. (2010, 2011), Zhao et al. (2014), Huang et al. (2017), Li et al. (2019); Aoyougou—Chen et al. (2012). In C and D, fields of subducted oceanic crust–derived adakites, thickened lower crust–derived Sr/Y rocks, and delaminated lower crust–derived Sr/Y rocks after Wang et al. (2006b). Data for SQM (Shenmutou, Quwushan and Maozangsì) and LDQX (Leigongshan, Deiqiangou, Quwushan and Xigela) high Sr/Y rocks are from Tseng et al. (2009) and Yu et al. (2015).
The LILE (e.g., Rb = 45.7–77.8 ppm; Th = 7.53–10.5 ppm) contents of the Haoquangou and Baimawa high Sr/Y rocks are distinctly higher than those of the predicted MORB-derived melts by geochemical modeling (Martin et al., 2014). Moreover, the Haoquangou and Baimawa high Sr/Y rocks possess more evolved Sr-Nd isotopic compositions than the Early Paleozoic ophiolites and slab-derived high Sr/Y rocks in the North Qilian and Central Qilian (Fig. 9A). However, derivation from subducted oceanic slab cannot be readily precluded considering the possible involvement of felsic crustal materials in their genesis. Here, three scenarios, including partial melting of MORB and subducted sediment, contamination of slab-derived melts by crustal materials, and mixing between slab-derived and crust-derived melts, were evaluated based on isotopic modeling and other geological and geochemical evidence. The roughly negative correlation between the Th/Ce and Th/Ce of the Haoquangou and Baimawa high Sr/Y rocks is in conflict with involvement of subducted sediment (Fig. 11A) (Hawkesworth et al., 1997). In addition, the involvement of a sediment component result in decreased Mg#, Sr/Y and εNd(t) values for oceanic slab-derived high Sr/Y rocks. However, Sr/Y ratios for the Haoquangou and Baimawa high Sr/Y rocks, with Mg# and εNd(t) decreasing, show a slight increase instead of a systematic decrease (Fig. 11F, Tables 1 and 2). Thus, melting of MORB and subducted sediment cannot account for the generation of high Sr/Y rocks in this study.

As shown in Figure 9A, the contamination of slab-derived melt by ~10%–20% felsic crustal materials represented by Qilian Precambrian basement and with different trace element and isotopic compositions can roughly reproduce the isotopic data of this study. However, for the Haoquangou and Baimawa high Sr/Y rocks, the sample with the lowest εNd(t) value also shows a lower εNd(t) value than the samples with higher εNd(t) values (Table 2; Figs. 11B and 11C), inconsistent with the gradual contamination of felsic crustal materials. Moreover, involvement of felsic crustal materials with evolved isotopic compositions into the slab-derived melts would result in the decrease of both εNd(t) and εNd(t) values for the generated melts. However, compared with the Early Paleozoic slab-derived high Sr/Y rocks in the Central Qilian (Yang et al., 2015), which have Sr–Nd isotopic compositions (εNd(t) = 0.7041–0.7069, εNd(t) = +2.8 to +3.8) similar to those of the slab-derived Aoyougou high Sr/Y rocks in the North Qilian (Fig. 9A), the Haoquangou and Baimawa high Sr/Y rocks show similar Hf isotopes (Figs. 7 and 9B), though with clearly more evolved Sr-Nd isotopic compositions (Figs. 9A and 9B).
9B), conflicting with the model of mixing slab-derived melts with crust-derived melts. Furthermore, there is no significant positive correlation between Sr/Y with Mg# or εNd(t) for the Haoquangou and Baimawa high Sr/Y rocks (Fig. 11F; Tables 1 and 2), which also does not support the model of involvement of crustal melts into slab-derived melts. Combined with their limited variation of major and trace element and Sr-Hf isotopic compositions (Figs. 5, 6, 7, and 9A; Tables 1 and 2), we suggest that the Haoquangou and Baimawa high Sr/Y rocks could not result from mixing of slab-derived and crust-derived melts. The arguments above, together with the relatively low Cr and Ni contents of the Haoquangou and Baimawa high Sr/Y rocks as compared with those of typical high Sr/Y rocks that were derived by oceanic crustal melting with different degrees of involvement of subducted sediment, overlying mantle, and crustal materials (Figs. 8C–8D), indicate that the Haoquangou and Baimawa high Sr/Y rocks could not be generated by slab melting.

As shown in Figures 5B and 5C, the major element compositions of the Haoquangou and Baimawa high Sr/Y rocks resemble those of the melts formed from melting experiments on the lower continental crust. Also, their Sr-Nd-Hf isotopes lie in the range of the Early Paleozoic granitoids that were suggested to be derived from mafic lower crust in the North Qilian (Figs. 7 and 9A). On the other hand, the Nd and Hf isotopic data of the Haoquangou and Baimawa high Sr/Y samples plot above the global terrestrial array and deviate toward higher εHf(t) at given εNd(t), showing decoupling of the Lu-Hf and Sm-Nd isotopic systems (Fig. 9B). This Nd-Hf decoupling was not observed in the Early Paleozoic slab-derived high Sr/Y rocks in the Central Qilian (Fig. 9B), but was identified in the Silurian newly emplaced (arc-related) mafic lower crust-derived Dulan TTG-like high Sr/Y rocks in the North Qaidam adjacent to the Qilian and the newly underplated juvenile basaltic lower crust-derived Lianhuashan high Sr/Y rocks in the eastern North Qilian. And, the decoupling was linked to the subduction-related metasomatism in the mantle source of the arc-related magma sources of the high Sr/Y rocks (Yu et al., 2012; Zhang et al., 2017b; Yu et al., 2019a, 2019b). Moreover, the Haoquangou and Baimawa high Sr/Y rocks also share similar Sr-Nd isotopic compositions with the
Early Ordovician mafic arc volcanic rocks in the Baiyin area (Wang et al., 2005a; Fig. 9A). Therefore, we suggest that the Haoquangou and Baimawa high Sr/Y rocks resulted from partial melting of relatively juvenile mafic rocks in the lower crust that could be the products of early arc magmatism. It should be noted that the high Sr/Y rocks (including those in this study) in the North Qilian, which were suggested to be derived from lower crust, show relatively variable Nd-Hf isotopic compositions (Figs. 7 and 9). Thus, the Early Paleozoic lower crust in the North Qilian could be inhomogeneous in composition and probably contained both juvenile and mature materials.

Constraints on Pressure Conditions for Magma Generation

Previous experimental studies have suggested that magma generation of high Sr/Y rocks by melting of mafic rocks requires high pressures (Rapp et al., 1991; Sen and Dunn, 1994; Rapp and Watson, 1995). Thus, many researchers linked the generation of high Sr/Y rocks to crustal thickening or lithospheric delamination (Xu et al., 2002; Chung et al., 2003; Wang et al., 2006b). However, previous experiments were mainly conducted on MORB-like sources with low Sr/Y ratios. Recent experiments on mafic continental crust and geochemical modeling have argued that, apart from melting pressure, source composition also plays an important role in the generation of high Sr/Y signatures for high Sr/Y rocks (Moyen, 2009; Qian and Hermann, 2013; Ma et al., 2015), which means that the higher the Sr/Y ratios of the sources, the lower the required pressures for the generation of high Sr/Y signatures. Thus, the continental crust can melt to produce high Sr/Y rocks at pressures lower than those for MORB-like rocks. For example, mafic continental crust can generate high Sr/Y melts through partial melting at a pressure of 10 kbar (equivalent to crustal thicknesses of ~33 km), and the metasedimentary sources (pelites or greywackes) may produce high Sr/Y melts at pressures as low as 5–10 kbar (Moyen, 2009; Qian and Hermann, 2013; Ma et al., 2015). Therefore, the occurrence of continental high Sr/Y rocks may not necessarily indicate crustal thickening, and detailed petrogenetic analysis should be done for high Sr/Y rocks before using them to indicate whether or not the continental crust was thickened.

Although metasedimentary rocks are able to generate high Sr/Y melts at low pressures (5–10 kbar), leaving garnet as a restite phase (Moyen, 2009), the geochemical data suggest that, as discussed previously, the Haoquangou and Baimawa high Sr/Y rocks were derived from mafic lower crust rather than metasedimentary sources. The low HREE contents and high La/Yb and Sr/Y ratios of high Sr/Y rocks derived by partial melting of mafic rocks are commonly attributed to the existence of garnet or amphibole in their sources. Here, we used trace element geochemical modeling to constrain the proportions of residual phases during the partial melting processes responsible for generation of the Haoquangou and Baimawa high Sr/Y rocks. The modal batch melting equation was used for modeling, and the compositions of the lower continental crust of Rudnick and Gao (2003) were assumed as the compositions of the source rock. The results show that residues of amphibole-and plagioclase-dominated mineral assemblage without garnet in the source cannot explain the low HREE contents and positive Sr anomalies of the Haoquangou and Baimawa high Sr/Y rocks, whereas modeled melts in equilibrium with the residual assemblage containing ~30% garnet and minor plagioclase (~10%) display trace element characteristics similar to those of the Haoquangou and Baimawa high Sr/Y rocks (Figs. 12A and 12B). Compared with the results of melting experiments on mafic lower crust with major elements similar to those of our assumed source in the geochemical modeling (Qian and Hermann, 2013), this coexisting garnet-bearing residual assemblage indicates high pressure (> 12.5 kbar, equivalent to crustal thicknesses of > 42 km) partial melting. Also, the Haoquangou and Baimawa high Sr/Y rocks show lower HREE...
Figure 12. (A–D) Primitive mantle-normalized trace element spider diagrams for the Haoquangou and Baimawa high Sr/Y rocks and modeled melts from mafic lower crust. In A and B, primitive mantle normalized values are from Sun and McDonough (1989); compositions of lower continental crust are from Rudnick and Gao (2003); proportions of the residual mineral phases refer to the estimation by Qian and Hermann (2013); the partition coefficients used for modeling calculations are listed in Data Repository Table DR7. In C and D, the modeled lower continental crust–derived melts at 10–15 kbar using partition coefficients obtained by melting experiments are from Qian and Hermann (2013). (E–G) (FeO+TiO2)/(Na2O+K2O), (FeO+Al2O3)/Na2O and Al2O3+CaO+FeO versus SiO2. (H) FeO versus CaO plots. In E–H, data for experimental melts coexisting with garnet are from Rapp et al. (1991), Sen and Dunn (1994), Patiño Douce and Beard (1995), Rapp (1995), Rapp and Watson (1995), Skjerlie and Douce (1995, 2002), Winther (1996), Springer and Seck (1997), Lopez and Castro (2001), Prouteau et al. (2001), Pertermann and Hirschmann (2003), Xiong et al. (2005), Zhou et al. (2005), Clemens et al. (2006), Klimm et al. (2008), Xiong et al. (2009), Adam et al. (2012), Gian and Hermann (2013), and Zhang et al. (2013a), and only melts with SiO2>53% were shown for comparison. All the experimental data have been normalized to 100%, anhydrous totals.
and higher La/Yb than the lower continental crust–derived melts at 10–12 kbar modeled by Qian and Hermann (2013) using mineral partition coefficients obtained by melting experiments (Figs. 12C–12D), suggesting that they were generated at higher pressures. On the other hand, the stability of garnet is in part controlled by the bulk composition of source rocks and it can be stable over a large range of pressures (20–10 kbar) during partial melting of mafic rocks (Wolff and Wyllie, 1994; Rapp and Watson, 1995). If the mafic sources are relatively enriched in Fe, Al, or Ca, garnet can occur as a residual phase at relatively low pressures (10–12 kbar), but in this situation, the coexisting melts are also characterized by relatively high Fe, Al, or Ca contents (Wolff and Wyllie, 1994; Rapp, 1995; Skjerlie and Douce, 1995, 2002). As shown in Figures 12E–12H, the major element compositions of the Haoquangou and Baimawa high Sr/Y rocks that were generated in the garnet stability field (Fig. 12A–12B) are different from those of experimental melts in equilibrium with garnet-bearing assemblages during melting of mafic rocks at 10–12 kbar, but are similar to those of melts coexisting with garnet at higher pressures (12.5–32 kbar). Moreover, the trace elemental compositions of the Haoquangou and Baimawa high Sr/Y rocks all fall into the range of the newly identified Silurian high Sr/Y leucosomes and tonalites in the adjacent North Qaidam (Fig. 6), which coexisted with their metagabbroic sources and melting residues and were constrained to form in the thickened lower crust at 15–18.5 kbar (Yu et al., 2012; Yu et al., 2019a, 2019b). Therefore, we suggest that the Haoquangou and Baimawa high Sr/Y rocks were derived from thickened crust.

**Secular Crustal Evolution in the Eastern North Qilian during the Late Ordovician to Silurian**

The variations of Sr/Y and La/Yb ratios of granitoids have been linked to crustal thickness changes in magmatic arcs and continental collisional belts (Chung et al., 2009; Schwartz et al., 2011; Chapman et al., 2015; Hu et al., 2017), although they can also be controlled by source compositions apart from melting pressure. As shown in the Sr/Y and La/Yb versus age diagrams (Figs. 13A and 13C), the Sr/Y and La/Yb ratios of the magmatic rocks in the eastern North Qilian are obviously high at ~457–430 Ma as compared with those of older or younger rocks, and many high Sr/Y plutons were generated during this period (Fig. 1B). Compared with the Haoquangou and Baimawa high Sr/Y granodiorites, they show similar or more evolved Sr-Hf isotopic compositions (Figs. 7 and 9A). In particular, their Hf isotopic compositions, like those of high Sr/Y rocks in this study, clearly plot below the depleted mantle evolution curve (Fig. 7), suggesting that continental crustal materials were also significantly involved in their genesis.

The 436–435 Ma Haoquangou and Baimawa high Sr/Y rocks with high SiO₂ (68.12–72.38%) and low Mg# (< 50) are suggested to be most likely derived from thickened lower crust as mentioned previously. As shown in Figure 14A, other 457–435 Ma high Sr/Y rocks in the eastern North Qilian also show relatively low Mg# and have been suggested to be the products of melting of thickened lower crust without interaction with mantle materials (Wang et al., 2005b; Tseng et al., 2009; Yu et al., 2015; Zhang et al., 2017b). In this regard, the wide distribution of the 457–435 Ma low-Mg high Sr/Y magmatism in the eastern North Qilian implies that the continental crust in the eastern North Qilian had been thickened during this period. However, from 434 to 430 Ma, the Mg# of the high Sr/Y rocks in the eastern North Qilian increased significantly as compared with those of the 457–435 Ma high Sr/Y rocks and the Sr/Y of the 434–430 Ma high Sr/Y rocks also decreased (Figs. 14A–14B), indicating more contributions from mantle materials in their formation. Considering their relationship with the related low-Mg high Sr/Y rocks and the petrologic and geochemical constraints, most of them were suggested to be produced by partial melting of delaminated lower continental crust followed by interaction with mantle peridotite (Tseng et al., 2009; Yu et al., 2015). Also, as shown in Figures 14C–14E, compared with those of older low-Mg high Sr/Y rocks in the eastern North Qilian, the overall higher Mg and Yb contents and lower SiO₂/Yb, Sr/Y, and Iₛₑ values of the younger high-Mg high Sr/Y rocks in the eastern North Qilian are also consistent with the interaction of lower crust–derived high Sr/Y melts with mantle materials. Thus, delamination of thickened lower crust probably occurred after thickening of the continental crust in the eastern North Qilian.

After 430 Ma, the Sr/Y and La/Yb ratios of magmatic rocks in the eastern North Qilian clearly decreased (Figs. 13A and 13C). Especially the 419–414 Ma A-type granites and their differentiates have been identified in the eastern North Qilian (Zhang et al., 2017b). As pointed out by Zhang et al. (2017b) and Xiong et al. (2012), most of these low Sr/Y granitoids in the eastern North Qilian could be generated by partial melting of relatively shallow crustal materials in an extensional setting. Therefore, strong crustal thinning could occur after delamination of thickened lower crust. Thus, the association of low-Mg high Sr/Y, high-Mg high Sr/Y, low Sr/Y and A-type granitoids with decreasing magma crystallization ages in the eastern North Qilian well record crustal thickening, delamination, and thinning during the Late Ordovician to Silurian period.

On the other hand, we use the Sr/Y and La/Yb ratios of the intermediate magmatic rocks to calculate the variation of crustal thickness in the eastern North Qilian during the Late Ordovician to Silurian according to the method proposed by Hu et al. (2017). The results show that the eastern North Qilian experienced crustal thickening beginning at ~460 Ma and crustal thinning after ~435–430 Ma (Fig. 14F), consistent with the conclusion constrained by the petrological and geochemical data mentioned above. Moreover, the Middle–Upper Silurian strata are absent in the eastern North Qilian (Xu et al., 2013), in line with strong uplift associated with lithospheric extension and mantle upwelling after the Early Silurian.

**Implications for Early Paleozoic Diachronous Ocean Basin Closure and Continental Collision from East to West in the North Qilian Belt**

The subduction polarity of the North Qilian Ocean is debated, and the proposed models include southward subduction (Peng et al., 2017a, 2017b), northward subduction (Xu et al., 2010; Yang et al., 2012; Song et al., 2013; Xia et al., 2016), and bidirectional subduction (Wu et al., 2011). However, considering the distribution of Early Paleozoic mid-ocean-ridge type ophiolites, high pressure metamorphic rocks, arc magmatic rocks, and back-arc ophiolites in the North Qilian from south to north (Liu et al., 2006; Tseng et al., 2007; Song et al., 2013; Xia et al., 2016), and the related sedimentary and structural characteristics, northward subduction of the North Qilian Ocean during the Ordovician was supported (Xu et al., 2010; Yang et al., 2012; Song et al., 2013; Xia et al., 2016). Nevertheless, the closure time of the North Qilian Ocean is still controversial, with inferred ages dominantly varying from the Late Ordovician to Late Devonian (Bian et al., 2001; Liu et al., 2006; Xiao et al., 2009; Yang et al., 2012; Song et al., 2013; Xia et al., 2016). It should be noted that most tectonic models proposed by previous researchers were based on the assumption that the evolution of the western and eastern parts of the North Qilian belt are synchronous, and thus neglect the differences between them along the orogenic strike. However, the results of this study combined with previous work show that distribution of Early Paleozoic high Sr/Y rocks is inhomogeneous along the North Qilian belt.
Figure 13. Plots of (A–B) Sr/Y versus age, (C–D) La/Yb versus age, and (E–H) age, Mg#, Sr/Y, and La/Yb versus longitude for the Late Ordovician to Silurian magmatic rocks in the eastern and western North Qilian. In B and D, the magmatic rocks from eastern North Qilian are indicated by light gray circles for comparison. Data sources are the same as in Figure 8.
Figure 14. (A–B) plots of Mg# and SiO$_2$ versus age, (C–E) plots of Sr/Y, Yb, and SiO$_2$/Yb*10$^4$ versus Mg# for the Early Paleozoic high Sr/Y rocks in eastern North Qilian, and (F) changes in calculated crustal thickness from Sr/Y and (La/Yb)$_n$ over time for the eastern North Qilian. Insets in D and E are plots of Yb versus $I_{yb}(t)$ (initial $^{87}$Sr/$^{86}$Sr calculated at 450 Ma) and SiO$_2$/Yb*10$^4$ versus $I_{yb}(t)$, respectively. Data sources in A–E: Wang et al. (2005b, 2006a, 2008), Tseng et al. (2009), Li (2012), Chen et al. (2015, 2016), Yu et al. (2015), Zhang et al. (2017b), and this study. Compiled and plotted data in F are included in Data Repository Table DR8. Present Moho depth of the eastern North Qilian is from Zhang et al. (2013b). Current global average thickness of continental crust is from Rudnick and Gao (2003). It should be noted that the present structure of continental crust in the Qilian orogen has been significantly affected by Cenozoic Indo-Eurasia collision. Especially the continental crust of the Qilian orogen has been obviously shortened and thickened due to the compression from the Indian plate. The light gray line in F shows the polynomial regression of calculated crustal thickness for all data.
Qilian belt: Early Paleozoic high Sr/Y rocks were lacking in the western North Qilian (Figs. 8A–8B, 13A–13D, and 13G–13H), except for the Aoyougou trondhjemites (~438 Ma) that probably derived from the exhumed oceanic slab and the newly reported small Jingtianshan granitic intrusion (~430 Ma) (Figs. 8A–8B, 9A, and 13; Chen et al., 2012; Li et al., 2019), while high Sr/Y plutons are abundant in the eastern North Qilian (Figs. 1B, 8A–8B, 13A–13D, and 13G–13H), which shows relatively enriched Sr/Nd isotopic compositions with a larger range of magma crystallization ages from ~457 to ~430 Ma (Figs. 9A and 14A–14B). This implies that evolution of the eastern and western parts of the North Qilian horst belt could be asynchronous. This inference is supported by the following facts. First, Early Paleozoic ophiolites are mainly distributed in the western part of the North Qilian and have been suggested to be the products of North Qilian Ocean seafloor spreading and development of back-arc basin at ~550–500 Ma and ~490–480 Ma, respectively (Tseng et al., 2007; Xia and Song, 2010; Song et al., 2013), while in the eastern North Qilian, the ophiolitic fragments were only reported in the Laohushan area (Qian and Zhang, 2001). Second, Early Paleozoic high-pressure/low-temperature metamorphic rocks (e.g., blueschist-to-eclogite-facies metamorphic rocks) were only exposed in the western part of the North Qilian, the protoliths of which are dominantly subduction-accretionary oceanic basalts, gabbros, greywackes, olistostrome, and pelagic/semi-pelagic sediments (Song et al., 2009, 2013). Finally, there are a large number of arc-volcanic and intrusive rocks represented by the Zhamashi (Alaska-type) mafic-ultramafic intrusions (~513 Ma), the Chaidanluo granitic batholiths (516–505 Ma), and the Dacha-Daba boninite complex (505–487 Ma) in the western North Qilian (Xia et al., 2012; Song et al., 2013; Chen et al., 2014), while arc-volcanic rocks are less exposed (Fig. 1B) and subduction-related (or Alaska-type) mafic-ultramafic intrusions are lacking in the eastern North Qilian.

Recently, the Middle Ordovician–Early Silurian sedimentary sequences in the Hexi-Corridor Basin, which was converted from a retro-arc basin to a foreland basin due to the collision between the Central Qilian block and the North China Craton, were studied in terms of their composition, detrital-zircon provenance, and formation environment (Yang et al., 2009; Xu et al., 2010; Yang et al., 2012). The mixing of detritus from both the Central Qilian Block and North China Craton has been detected within Middle–Late Ordovician clastic sedimentary rocks in the eastern Hexi–Corridor Basin (Xu et al., 2010). These, combined with detrital zircon geochronological data and the regional angular unconformity, indicate that the initial collision in the eastern North Qilian occurred in the Middle Ordovician (~470–460 Ma), corresponding to the Gulang movement (Xu et al., 2010). As discussed above, the eastern North Qilian experienced clear crustal thickening from ~460 Ma (Fig. 14F), which could be the response to the initial collision in the eastern North Qilian. In contrast, the Late Ordovician in the western part of the Hexi-Corridor Basin is dominated by carbonate sediments (Feng and He, 1996), indicative of an open ocean environment. For the western Hexi-Corridor Basin, the initial mixing of the Central Qilian Block and North China Craton detritus was identified in the Early Silurian sandstones (Yang et al., 2009, 2012), and thus the collision in the western North Qilian probably commenced at the end of the Ordovician to Early Silurian. Moreover, in the western North Qilian, the subduction-induced high pressure metamorphism lasted from ~489 to 446 Ma, as indicated by reliable geochronological data for the eclogite- and blueschist-facies rocks (Song et al., 2004; Liu et al., 2006; Zhang et al., 2007), also suggesting that the collision in the west of the North Qilian occurred no earlier than the end of the Ordovician. Therefore, the diachronous collision from east to west could have occurred in the North Qilian during the Early Paleozoic and could be responsible for the differential distribution of Early Paleozoic high Sr/Y magmatism (Figs. 13A–13D and 13G–13H) and other geological differences between the eastern and western North Qilian.

High Sr/Y magmatism in the western North Qilian occurred much later than in the eastern North Qilian (Fig. 13A and 13B). Also, except for the Aoyougou trondhjemites derived by decompression melting of exhumed eclogite (meta-oceanic crust) (Figs. 8A–8B, 9A, 13B, and 13G) and the newly reported Jingtianshan granites (Chen et al., 2012; Li et al., 2019), the other magmatic rocks generated in the western North Qilian during the Late Ordovician to Silurian all feature low Sr/Y ratios (Figs. 8A, 13B, and 13G). Moreover, unlike in the eastern North Qilian, the La/Yb ratios of the granitoids in the western North Qilian do not show obvious variation from the Late Ordovician to Silurian (Figs. 13D and 13H). These, combined with the duration time and volumes of the high Sr/Y magmatism, the absence of the extension-related magmatism (e.g., A-type granite), and the fact that the Lower to Upper Silurian is completely preserved in the western North Qilian (Xu et al., 2013), suggest that crustal thickening, thinning, and uplift in the western North Qilian were not as strong as in the eastern North Qilian during the Early Paleozoic period. On the other hand, the occurrence of detrital zircons of 550–500 Ma corresponding with the age of the North Qilian ophiolites within the Early–Middle Devonian sandstones in the eastern North Qilian (Xu et al., 2013) and the distinctly higher FeO, MgO, Cr, Ni, Sc, and V, lower Zr and Hf contents, and higher Eu*/Eu ratios of the Early–Middle Devonian clastic sedimentary rocks in the eastern North Qilian and more metamorphic fragments within them as compared with those of the time equivalent strata in the western North Qilian (Hou et al., 2018) indicate that the eastern North Qilian could have experienced stronger uplift and erosion than the western North Qilian, which could account for the fewer occurrences of Early Paleozoic ophiolites, high pressure metamorphic rocks, and arc-related magmatic rocks in the eastern North Qilian.

Overall, we suggest that the Early Paleozoic collision in the North Qilian was diachronous from east to west (Fig. 15), and the eastern North Qilian experienced stronger collision-related processes (e.g., crustal thickening and post-collisional extension) than the western North Qilian where subduction-accretionary processes predominated. This diachronous collision could have resulted in the inhomogeneous intensity of orogenesis and thus inhomogeneous uplift and erosion between the eastern and western North Qilian. The stronger crustal thickening in the eastern North Qilian resulted in the widespread occurrence of Early Paleozoic high Sr/Y rocks. Our results also suggest that diachronous collision may lead to the large difference in magmatism and deep crustal processes along the strike of the orogenic belts.

**CONCLUSIONS**

The Haoquangou and Bainawu granodiorites from the eastern North Qilian have magma crystallization ages of 436 and 435 Ma, respectively. They have high Sr/Y ratios, coupled with low Y and HREE contents and relatively enriched isotopic compositions. These high Sr/Y rocks were generated by partial melting of relatively juvenile mafic rocks in a thickened lower crust in a post-collisional setting. Petrological and geochemical data, in combination with the calculation of crustal thickness variation, show that the crust in the eastern North Qilian experienced clear thickening and thinning from the Late Ordovician to Late Silurian. Combined with previous work, we suggest that diachronous collision proceeding from east to west in the North Qilian, which probably resulted in stronger crustal thickening and post-collisional extension in the eastern North Qilian, was responsible for the
in-homogeneous distribution of the Early Paleozoic high Sr/Y rocks and other large differences in the geologic features between the eastern and western parts of the North Qilian. This study also implies that diachronous collision may lead to the large differences in magmatism and deep crustal processes (apart from metamorphism, structural development, sedimentation, etc.) along the strike of the orogenic belts.

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