Research Article

Origin of the Miocene Adakitic Rocks and Implication for Tectonic Transition in the Himalayan Orogen: Constraints from Kuday Granitoid Porphyry in Southern Tibet

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Postcollisional adakitic magmatism in the Himalayan Orogen provides a probe into the evolution of the collisional orogen. During the Miocene, the Himalayan Orogen underwent a tectonic transition, which was characterized by a series of tectonic events, including the activity of the North-South Trending Rift, exhumation of eclogite, rapid uplift of the orogen, and the extensive adakitic rocks. In this study, we reported the geochemistry and geochronological data of the Kuday dikes intruding into the Tethys Himalayan Sequence near the Sakya Dome of southern Tibet. The Kuday dikes are granitoid porphyries with zircon U-Pb ages of ca. 11 Ma. The Kuday granitoid porphyry dikes have high SiO₂ (63.01–68.41 wt.%) and Al₂O₃ (17.31–19.87 wt.%) but low Mg (0.88–1.41 wt.%), Mg# (36–50), Ni (2.8–19.3 ppm), and Cr (2.9–26.4 ppm), indicating no input of mantle material. They have high Sr (934–1881 ppm), (La/Yb)N (18.84–113.13), and Sr/Y ratios (89.25–305.85) but low K₂O/Na₂O ratios (0.17–0.79), indicating that they are adakitic affinity. They display initial 87Sr/86Sr ratios of 0.707–0.711 and εNd(t) values of -3.7–6.7. These geochemical signatures indicate that the Kuday granitoid porphyrite dikes were derived from the partial melting of the thickened lower crust of the Himalayan Orogen. Partial melting of the thickened lower crust requires additional heat, so the delamination model with lithospheric mantle thinning and asthenospheric upwelling is proposed to explain the formation of the Kuday adakitic rock. The delamination model can also provide a reasonable explanation for the tectonic events during the Miocene in the Himalayan Orogen.

1. Introduction

Since the initial collision of the Eurasian Plate and Indian Plate at approximately 55-65 Ma, the magnificent Himalayan Orogen has become a natural material for observing the tectonic evolution of the collisional orogens [1–8]. Postcollisional igneous rocks provide substantial constraints on the tectonic evolution, geodynamic processes, and thermal structure of the Himalayan Orogen. Previous studies of the Himalayan postcollisional rocks mainly focused on leucogranite and proposed various models for Himalayan evolution during the Miocene [9–14]. In recent years, there is growing attention to the Miocene adakitic rocks of the Himalayan Orogen, and the characteristics of the adakitic rocks allow them to provide more details about the crustal thickness and crust-mantle interactions, yielding more evidence for the tectonic evolution of the Himalayan Orogen [15–20].

Defant and Drummond [21, 22] first introduced the term “adakite” to describe a class of magmatic rocks originating directly from young subducted oceanic basalt, which were geochemically characterized by intermediate to high silica (>56 wt.% SiO₂), low K, and depleted heavy rare earth elements (HREE) and Y but high Na and Sr. Rapp et al. [23] and Martin [24] suggested that these geochemical features were attributed to the origin of the partial melting of eclogite...
or garnet amphibolite. As the study of adakites progressed, several models for adakite petrogenesis have been proposed, including partial melting of the basaltic portion of the subducting oceanic crust [21, 22, 25], partial melting of the thickened lower crust [26–29], partial melting of metasomatized mantle [30, 31], and assimilation and fractional crystallization (AFC) of mantle-derived magmas [32–34]. Regardless of which model is used, the formation of adakites is associated with crust-mantle interactions and deep thermal structures, making them a powerful tool for our understanding of geodynamics and tectonic evolution.

Two periods of Cenozoic adakitic rocks were recognized in the Himalayan Orogen: Eocene (46–39 Ma) [11, 35–37] and Miocene (20–11 Ma) [15–20, 38]. The former was thought to be a partial melting of the lower crust induced by the breakoff of the Neo-Tethyan slab [36, 37], which was supported by oceanic island basalt-type magmatism [39] and eclogites [40]. However, the formation mechanism and source of the Himalayan Miocene adakitic rocks are still controversial, and present-day models include (1) partial melting of the thickened mafic lower crust of the Indian Plate [15, 18]; (2) partial melting of the thickened mafic lower crust, mixed with mantle-derived juvenile magma [19, 20]; and (3) magmatic mixing of three representative geochemical end members (subcontinental lithospheric mantle, mid-lower crust, and mid-upper crust) of the Asian Plate and intruding into Tethyan Himalayan Sedimentary Sequence (THS) along the channel flow [38]. Therefore, more detailed analytical and comparative work on the Himalayan adakitic rocks is necessary.

In the South Lhasa Terrane, adjacent to the Himalayan Orogen, Chung et al. [26] first systematically studied post-collisional adakitic rocks and constrained the ages of these rocks, ranging from 26 to 10 Ma, which were contemporaneous with Himalayan Miocene adakitic rocks. These two adjacent blocks, the Himalayan Orogen and the Lhasa Terrane, are considered to have experienced similar deep lithospheric geodynamic processes during the Miocene [19, 20]. In the past two decades, a lot of excellent work has been performed on the South Lhasa Miocene adakitic rocks, and several geodynamic models have been proposed to interpret the Miocene tectonic evolution of the southern Tibetan region: (1) delamination of thickened lithospheric root [26–29, 41–44], (2) subducted Indian continental slab breakoff [19, 20, 28–31, 45–47] or rollback [38, 48], and (3) slab-tearing of subducted Indian Plate [29, 46, 49, 50].

Compared to the extensive studies on the Miocene adakitic rocks of the South Lhasa Terrane, there are few studies on the Miocene adakitic rocks of the Himalaya. The Kuday granitoid porphyrite dikes are a series of dikes intruded into THS. King et al. [38] have reported the geochronological and geochemical characteristics of the Kuday dikes, yet the origin and tectonic significance of these dikes are still obscure. In this study, we report new data of whole-rock major and trace elements, Sr–Nd isotopes, and zircon U–Pb ages for these porphyrites. These results, combined with the summary of other Miocene adakitic rocks in the Himalayan Orogen and Lhasa Terrane, provide a valuable perspective to constrain and understand the tectonic evolution and deep dynamic processes of the Himalayan-Tibetan Orogen during the Miocene.

2. Geological Background

Multiple blocks amalgamated into the Eurasian continent, gradually forming the present-day tectonic pattern of the Tibetan Plateau, since the Paleozoic. Several E-W trending suture zones divide the Tibetan Plateau into four terranes, including Songpan-Ganzi Terrane, Qiangtang Terrane, Lhasa Terrane, and Himalayan Orogen from north to south [51]. The Himalayan Orogen, a result of the most spectacular orogenic event of the Cenozoic, was created by the convergence between the Indian Plate and the European Plate [2, 8]. The Himalayan Orogen consists of four lithotectonic units, which are, from south to north, Siwalik Group, Lower Himalayan Sedimentary Sequence (LHS), Great Himalayan Crystalline Complex (GHC), and THS (Figure 1(a)) [2]. The Siwalik Group is a set of foreland basin sediments from the Miocene to Pliocene [3]. The LHS is composed of low-graded metasediments, metavolcanic rocks, and augengneisses, and radioisotope dating results indicated that the ages of these rocks range from 1850 Ma to 850 Ma [52]. The GHC is thought to be exposure of amphibolite- to granulite-facies metamorphic rocks from the middle-to-lower crust of the Himalayan Orogen, and the protoliths of these metamorphic rocks formed in the late Proterozoic to early Cambrian [53–56]. The THS is a sequence of late Proterozoic to Eocene marine sediments [2, 57]. These units are subdivided by four faults systems, including the South Tibetan Detachment System (STDS), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT) [2, 4].

A number of discontinuous North Himalayan Gneiss Domes (NHGD) are distributed in the THS [58]. These NHGD exposed the high-grade metamorphic rocks that form a natural window of insight into the structure of the Himalayan Orogen [11, 14, 59–64]. Sakya Dome, one of the NHGD, is located in the central part of the Himalayan Orogen and has been studied well [10, 38, 60–62]. The Sakya Dome has a core-mantle-rim structure and contains gneisses and leucogranites in the core, medium-grade metamorphic rocks and shear zone in the mantle, and THS sedimentary rocks in the rim [60].

3. Field Description and Petrography

3.1. Field Description. The Kuday granitoid porphyrite dikes are irregularly intruding into the north of the Sakya Dome shear zone and its overlying THS, ranging from ~1 to ~10 m in width (Figure 2). The wallrock comprises slate, phyllite, metasandstone, and siltstone [38, 60]. Two samples (19NSK-39 and 19NSK-40) were selected for zircon U–Pb dating, and 17 samples from 4 dikes were collected for bulk geochemical analyses (Figure 1(b)). Field investigations indicated that Kuday granitoid porphyrite dikes and the surrounding rocks have clear boundaries, and the dikes contained little or no wallrock material (Figure 2), which suggested limited assimilation. Ascending melts for dike
are fast and retain most information of source characteristics and dynamic processes [65].

3.2. Petrography. The Kuday dikes are grey colored, and all samples display a typical porphyritic texture. The phenocrysts in a portion of the samples are relatively large and consist of plagioclase (5 mm–10 mm, Figure 3(a)), hornblende (ca. 30 mm; Figure 3(b)), and biotite (ca. 0.5 mm; Figure 3(c)). The phenocrysts from other samples are mainly relatively small plagioclase (1.5 mm–3 mm) and biotite (ca. 0.8 mm).

**Figure 1:** (a) Regional tectonic sketch map of the Himalayan Orogen and Gangdise batholith (modified from Li et al. [18] and Lin et al. [20]); (b) geological map of Kuday area and sample locations. STDS: South Tibet Detachment System; MCT: Main Central Thrust; MFT: Main Frontal Thrust; MBT: Main Boundary Thrust. The Miocene adakitic rocks in southern Tibet: 1: Mayum (~16.67 Ma [20]); 2: Lasa (~16.52 Ma [18]); 3: Kuday (11–12 Ma [38] and this study); 4: Gyagze and Bendui (11–12 Ma [19]); 5: Langkazi enclave (11–12 Ma [86]); 6: Yardoi (17.7–20 Ma [15–17]); 7: Yadong orbicular diorite (14–18 Ma [103]); 8: Shiduo (~16 Ma [104]); 9: Bangba (~17 Ma [76]); 10: Manasarowar and Gagar (~17 Ma [41]); 11: Daggya (18–20 Ma [43]); 12: Zhunnu (~12.3 Ma [105]); 13: Nanmu (~14.3 Ma [106]); 14: Xigaze (11.8–13.6 Ma [44]; 18–15 Ma [26]); 15: Maquing (15–10 Ma [80]); 16: Nimu (~12 Ma [28, 76]); 17: Nanmu (16–12 Ma [28, 76]); 18: Lakang’e (11–14 Ma [68]); 19: Qulong (18–17 Ma [28]); 20: Jiama (15–17 Ma [28]).
0.5 mm; Figure 3(d)). It is worth noting that some of the hornblende phenocrysts were replaced by biotite, forming hornblende pseudomorph (Figure 3(c)). The hornblende phenocrysts are green to brown with two clear cleavages (Figure 3(b)). The plagioclase phenocrysts form euhedral and tabular crystals and rhythmic zoning (Figure 3(a)). The matrix of the Kuday granitoid porphyrite dikes comprises quartz (~20%), plagioclase (~25%) and biotite (~5%), and accessory minerals including zircon, apatite, and Ti-Fe oxides.

4. Analytical Method

4.1. Zircon U-Th-Pb Dating. Zircon grains were separated, using standard heavy-liquid and magnetic techniques, and handpicked under a binocular microscope. Selected zircon grains were embedded in a 2.54 cm epoxy resin disk, and these grains were polished to expose their centers. Cathodoluminescence (CL) imaging was utilized to reveal the internal structure of the zircon grains and determine the target. CL images were taken from the Key Laboratory of Orogenic Belts and Crustal Evolution, School of Earth and Space Sciences, Peking University, China, using a Quanta 200 FEG Scanning Electron Microscope (SEM).

The U-Th-Pb isotope and elemental analyses were conducted by the LA-ICP-MS instrument at the Wuhan Sample Solution Analytical Technology Co., Ltd., following the procedures presented by Lin et al. [20]. The spot size and the laser frequency were set to 24 μm and 5 Hz, respectively. Standard zircon 91500 was utilized to correct the isotope fractionation, and standard NIST610 was used for the trace element calibration.

ICPMSDataCal software was used to calculate isotopic ratios and elemental concentrations [66]. Concordia diagrams and weighted mean age diagrams were plotted by using Isoplot 3.0 [67]. The analytical results presented in Table S3 were 1σ, and the errors of the Concordia diagrams and weighted mean ages were 2σ.

4.2. Bulk Rock Major and Trace Element Analyses. Whole-rock major element concentrations were obtained by X-ray fluorescence, and trace element concentrations, including rare earth elements, were obtained by a Perkin-Elmer ELAN 300D inductively coupled plasma mass spectrometer (ICP-MS) at the Nanjing Hongchuang Geological Exploration
Technology Service Co., Ltd. Analytical precision and accuracy for major elements are better than 5% by XRF, and analytical precision and accuracy for trace elements are better than 10% by ICP-MS. Whole-rock major and trace element data are listed in Table S1.

4.3. Sr-Nd Isotope Composition Analyses. Sr-Nd isotope analyses were conducted by Neptune Plus MC-ICP-MS at the Nanjing Hongchuang Geological Exploration Technology Service Co., Ltd. The standard \( ^{88}\text{Sr}/^{86}\text{Sr} \) value (0.723769) and \( ^{146}\text{Nd}/^{144}\text{Nd} \) value (0.7219) were used to correct the mass fractionation of the measured \( ^{87}\text{Sr}/^{86}\text{Sr} \) and \( ^{143}\text{Nd}/^{144}\text{Nd} \) values based on the exponential law. Standard NIST SRM 987 was measured during the analysis of the Sr isotope, and the standards yielded an \( ^{87}\text{Sr}/^{86}\text{Sr} \) ratio of 0.710244 ± 0.000022 (2SD, \( n = 32 \)), within error to their published values (0.710241 ± 0.000012). Standard JNd-i-1 was used during analysis of the Nd isotope, which yielded a \( ^{143}\text{Nd}/^{144}\text{Nd} \) ratio of 0.512118 ± 0.000015 (2SD, \( n = 31 \)) within error to their published values (0.512115 ± 0.000007). Sr-Nd isotope analytical data are listed in Table S2.

5. Results

5.1. Zircon U-Th-Pb Dating. Zircon of two samples (19NSK-39 and 19NSK-40) from Kuday granitoid porphyrite dikes was selected for zircon LA-ICP-MS U-Pb dating. Most of the zircons are colorless, euhedral, and 100–200 μm in length. CL images reveal that most zircons show clear oscillatory zoning, and some of them show fan-shaped zoning (Figures 4(a) and 4(b)). Although some of the zircons have a core-rim structure, with bright cores and dark rims, well-developed oscillatory zoning in a dark rim, relatively high Th/U (most >0.1). Zircon U-Pb data with concordance >90% are regarded as reliable and selected to make the Concordia diagrams and determine the weighted mean age.

The zircon grains from sample 19NSK-39 yield concordant ages from 10.8 to 1286.9 Ma (Table S3); however, the dominant apparent ages are concentrated at ca. 11 Ma.
These zircons from 19NSK-39 have U concentrations of 67–3178 ppm, Th concentrations of 3–814 ppm, and Th/U ratios of 0.01–0.9. Analysis of fourteen spots yielded a weighted mean 206Pb/238U age of 11.31 ± 0.32 Ma (2σ; MSWD = 3.5, n = 14; Figure 4(e)), with apparent 206Pb/238U age ranging from 10.5 to 11.9 Ma (Figure 4(e)). The zircon grains from sample 19NSK-40 yield apparent ages from 10.53 to 2452.31 Ma (Table S3; Figure 4(c)).
5.2. Whole-Rock Geochemistry. The major element compositions of the Kuday granitoid porphyrite dikes are normalized to 100% on a volatile-free basis. The granitoid porphyries exhibit high SiO$_2$ (63.01–68.41 wt.%), Al$_2$O$_3$ (17.31–19.87 wt.%), and TiO$_2$ (2.24–4.77 wt.%), high CaO (1.12–4.61 wt.%) and Na$_2$O (4.2–5.49 wt.%), but low MgO (0.88–1.41 wt.%), TiO$_2$ (0.59–0.99 wt.%), and P$_2$O$_5$ (0.29–0.61 wt.%), and thus low Mg# (100 × molar MgO/(MgO + FeO)) (36.32–49.55). They contain moderate K$_2$O contents of 0.84 wt.% to 3.39 wt.%, and most of the samples were plotted in calc-alkaline to high K calc-alkaline field (Figure 5(a)). These samples were plotted in trachyte, dacite, and andesite fields on total alkali versus silica diagram (Figure 5(b)), similar to other Himalayan Miocene adakitic rocks [15–20]. All samples have low K$_2$O/Na$_2$O ratios of 0.17 to 0.79 (Figure 5(c)). Their relatively low A/CNK (molar Al$_2$O$_3$/[CaO + Na$_2$O $+$ K$_2$O]) values of 0.89 to 1.33 but high A/KN (molar Al$_2$O$_3$/[Na$_2$O $+$ K$_2$O]) values of 1.54 to 2.16 indicate that the Kuday granitoid porphyrite dikes are metaluminous to peraluminous (Figure 5(d)).

The Kuday granitoid porphyrite dikes have moderate total REE and enriched light REE (LREE, 103.306–286.406 ppm) but depleted heavy REE (HREE, 8.556–15.354 ppm). LREE and HREE are highly fractionated patterns on the chondrite-normalized REE diagram (Figure 6(a)) with nearly no Eu anomalies (0.80–0.98). The Kuday granitoid porphyrite dikes display enriched large ion lithophile elements (LILE, e.g., Rb, Sr, and Ba; Figure 6(b)) but depleted high field strength elements (HFSE, e.g., Nb, Ta, Zr, and Hf; Figure 6(b)). They have obvious positive Sr anomalies and high Sr (934.252–1881.577 ppm) and La (21.360–99.461 ppm) but low Y (5.537–16.420 ppm) and Yb (0.375–1.465 ppm) and thus high Sr/Y ratios (89.29–305.85) and (La/Yb)$_N$ value (18.84–113.13), indicating an adakitic affinity (Figure 7) [21, 22]. Most samples are within the adakite field on (La/Yb)$_N$ versus Yb$_N$ and Sr/Y versus Y diagrams (Figure 7). Furthermore, they show low Ni (2.793–19.251 ppm) and Cr (2.862–26.398 ppm) contents.

5.3. Sr-Nd Isotope Geochemistry. The initial Sr-Nd isotopic ratios are calculated based on the weighted mean age of sample 19NSK-39 ($t = 11.31$ Ma), and the initial Sr-Nd isotopic ratios are presented in Figure 8. All of the samples display homogeneous Sr-Nd compositions. The Kuday granitoid porphyrite dikes have initial $^{87}$Sr/$^{86}$Sr values ranging from 0.707 to 0.711 and $\varepsilon_{Nd}(t)$ values ranging from -3.7 to -6.7. Two stages of Nd model age (TDM2) of these rocks range from 1005 to 1260 Ma.

6. Discussion

6.1. Origin of the Kuday Granitoid Porphyrite Dikes. The Kuday granitoid porphyrite dikes are characterized by intermediate to high SiO$_2$ and high Al$_2$O$_3$ and Sr, depleted in HREE and LREE but enriched in LREE and LILE, leading to high ratios of Sr/Y and (La/Yb)$_N$, which is consistent with the adakitic rock defend by Defant and Drummond [21, 22]. Geodynamic models for adakitic rocks include (1) partial melting of subducted oceanic crust in island or continental arcs [20, 21, 68, 69] or upper mantle metasomatized by the slab-derived melts/fluids [30, 31, 70], (2) melting of thickened lower crust [26–29, 41–44] or melting of delaminated crust [71, 72], and (3) assimilation and fractional crystallization (AFC) processes of mantle-derived parental basalt [32, 33].

Adakitic rocks related to oceanic slab melting are often found in the tectonic setting of islands or continental arcs and on the side of active continental margin [20, 21, 69]. Similarly, the upper mantle metasomatized by the slab-derived melts/fluids also occurs on the side of the active continental margin [30, 31]. However, the Himalayan Orogen was a passive continental margin. Previous studies have shown that closure of the Neo-Tethys Ocean and initial Indo-Asia collision occurred at 65–55 Ma [5–7], and break-off of the subducted Neo-Tethys Ocean plate occurred at 45–38 Ma [36, 37, 39, 40, 47]. With comprehensive consideration of the regional geological setting, subducted-related adakitic rocks cannot be formed in the Himalayan Orogen during the Miocene, and geological signatures also disprove the hypothesis that the Kuday adakitic rocks originated from subducted ocean slab melting. The slab-derived adakitic melts display high MgO, Cr, Ni contents, and Mg# but relatively low SiO$_2$ and MORB-like Sr-Nd isotope (Figures 5, 8, and 9) [20, 21, 68, 69]. The adakitic rocks derived from the metasomatized mantle exhibit high K and Mg# (>50) [70]. In addition, potassic and ultrapotassic rocks are widely recognized as products of metasomatized lithospheric mantle melting [46], and the Miocene ultrapotassic rocks which were found in the Himalayan Orogen exhibit initial $^{87}$Sr/$^{86}$Sr ratios of 0.719–0.721 and $\varepsilon_{Nd}$ values of -10.7 to -10.8 [73]. The Kuday adakitic rocks have low Mg, Ni, Cr contents, and Mg# but relatively low Sr and MORB-like Sr-Nd isotope (Figures 5, 8, and 9) [20, 21, 68, 69]. The adakitic rocks derived from the metasomatized mantle exhibit high K and Mg# (>50) [70]. In addition, potassic and ultrapotassic rocks are widely recognized as products of metasomatized lithospheric mantle melting [46], and the Miocene ultrapotassic rocks which were found in the Himalayan Orogen exhibit initial $^{87}$Sr/$^{86}$Sr ratios of 0.719–0.721 and $\varepsilon_{Nd}$ values of -10.7 to -10.8 [73]. The Kuday adakitic rocks have low Mg, Ni, Cr contents, and Mg# but relatively low Sr and MORB-like Sr-Nd isotope (Figures 5, 8, and 9) [20, 21, 68, 69]. The adakitic rocks derived from the metasomatized mantle exhibit high K and Mg# (>50) [70]. In addition, potassic and ultrapotassic rocks are widely recognized as products of metasomatized lithospheric mantle melting [46], and the Miocene ultrapotassic rocks which were found in the Himalayan Orogen exhibit initial $^{87}$Sr/$^{86}$Sr ratios of 0.719–0.721 and $\varepsilon_{Nd}$ values of -10.7 to -10.8 [73].
(Figures 10(a)–10(e)). In addition, based on the incompatibility of Zr and compatibility of Sm in hornblende, Zr/Sm ratios increase during fractional crystallization of hornblende [22]. A slight correlation between the Zr/Sm ratios and SiO$_2$ indicates that the fractional crystallization of hornblende is not the main factor for the formation of the Kuday adakitic rocks (Figure 10(f)). Eu is a compatible element for feldspar, and the fractional crystallization of feldspar results in significant negative Eu anomalies. Therefore, constant Eu/ Eu* indicates the absence of feldspar fractional crystallization (Figure 10(g)). Finally, no correlation between $\varepsilon_{Nd}(t)$ /initial $^{187}$Os/$^{188}$Os and SiO$_2$ indicates little modification of the Kuday adakitic rocks by crustal contamination (Figures 10(h) and 10(i)). Consequently, assimilation and

![Figure 5: Geochemical classification diagrams for the Kuday granitoid porphyrite dikes, Lhasa and Himalayan Miocene adakitic rocks. (a) K$_2$O versus SiO$_2$ diagram, after Peccerillo and Taylor [107]. Classification lines are from Rickwood [108]. (b) Total alkali versus silica diagram, after Le Bas et al. [109]. Alkali-silica diagram modified from Irvine and Baragar [110]. (c) K$_2$O/Na$_2$O versus SiO$_2$. (d) A/NK versus A/CNK diagram. The fields of subduction-related and lower crust-derived adakitic rocks are from Guan et al. [111] and Li et al. [18]. Data for Lhasa Miocene adakitic rocks are from Miller et al. [41], Hou et al. [28], Qu et al. [68], Guo and Wilson [46], Gao et al. [30, 31], Xu et al. [106], Chen et al. [76], Chen et al. [112], Zeng et al. [105], and Xu et al. [44]. Data for Himalayan Miocene adakitic rocks are from King et al. [38], Zeng et al. [15–17], Li et al. [18], Ji et al. [19], and Lin et al. [20].](http://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/doi/10.2113/2022/8061474/5540611/8061474.pdf)
fractional crystallization are not the main cause of the formation of the Kuday granitoid porphyrite dikes.

The adakitic melts derived from delaminated lower crust show relatively high MgO contents and Mg#, due to the interaction of the adakitic melt and mantle material [71, 74]. In addition, compatible elements (Ni, Cr) are excellent indicators to identify the presence or absence of mantle-crust interaction for adakitic rocks [71]. These features are inconsistent with Kuday adakitic rocks, so the delaminated lower crust model can be excluded. The most accepted model is the partial melting of the thickened lower crust [26–29]. Kuday adakitic rocks have low Mg (0.88–1.41 wt.%, <3 wt.%), Cr (2.862–26.398 ppm, <100 ppm), Ni (2.793–19.251 ppm, <20 ppm) contents, and Mg# (36–49, <50), which are consistent with experimental petrology results of metabasalts and eclogites [23, 74]. Guo et al. [75] simulated quantitatively the trace element using a nonmodal batch melting model, and the result showed that partial

**Figure 6**: Primitive mantle-normalized trace element (a) and chondrite-normalized REE (b). Normalization values are from Sun and McDonough [113]. Data sources are the same as Figure 5.
melting of thickened lower crust can form this type of adakitic rocks. In addition, the enriched radioactive Sr and Nd isotope of these adakitic rocks indicate an origin of the continent crust [26], and their initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$ values are close to the isotopic compositions of the adakitic rocks originating from the thickened lower crust [18, 20].

![Figure 7](image_url)

**Figure 7:** (a) Sr/Y versus Y diagram; (b) (La/Y)$_N$ versus Yb$_N$. Field of adakite and arc magmatic rocks is from Defant and Drummond [21] and Castillo et al. [32]. Data sources are the same as in Figure 5.

![Figure 8](image_url)

**Figure 8:** $\varepsilon_{\text{Nd}}(t)$ versus initial $^{87}\text{Sr}/^{86}\text{Sr}$ diagram. Field of the subduction-related adakite, IYSZ MORB, and lower crust is modified from Hou et al. [28]. Data of Linzizong Volcanic Sequence in Lhasa are from Mo et al. [114]; Data of Southern Gangdese Batholiths are from Ji et al. [115]. Data of Miocene potassic and ultrapotassic rocks in Lhasa Terrane are from Guo and Wilson [46] and reference therein. Data for Miocene adakitic rocks in Lhasa Terrane and Himalayan Orogen are the same as Figure 5.
It is certain that the Kuday adakitic rocks originated from partial melting of the lower crust. King et al. [38] proposed that crust flow transported Asian crust-related melts to the Himalayan Orogen, which formed these adakitic rocks, and this model was supported by Chen et al. [76]. The evidence supporting this model is the initial $^{87}$Sr/$^{86}$Sr ratios and $\varepsilon_{Nd}$ values of the Kuday adakitic rocks plotted in the mixing line of Asian plate subcontinental lithospheric mantle and Asian plate upper crust [38]. However, there are several problems within this model. (1) There are systematic differences in Sr-Nd isotope between the adakitic rocks of Lhasa Terrane and Himalayas. The Himalayan adakitic rocks have more enriched radioactive Sr and Nd isotope than those from Lhasa Terrane (Figure 8). (2) The adakitic rocks of Lhasa Terrane are often formed with the involvement of ancient Indian continental crust compositions [2] or potassic/ultrapotassic rocks [28], which resulted in some Lhasa adakitic rocks having high K (Figures 5(a) and 5(c)). Himalayan adakitic rocks always have low K2O and K2O/Na2O ratios, indicating that they underwent no or limited assimilation with ancient crustal sedimentary material (Figures 5(a) and 5(c)). (3) The channel flow model was proposed by Beaumont et al. [77, 78] to mainly interpret the extrusion of the GHC. However, evidence of metamorphic rocks indicates that ductile channel flow ceased at ca. 14-12 Ma [79]. In addition, no evidence was found in

Figure 9: (a) Mg versus SiO2 diagram; (b) Mg# versus SiO2 diagram; (c) Ni versus SiO2 diagram; (d) Cr versus SiO2 diagrams. Subduction-related and lower crust-derived adakite fields are after Wang et al. [72] and Guan et al. [111]. Data sources are the same as Figure 5.
the GHC that the channel flow carried Asian material into Himalayan Orogen. (4) If material derived from the Asian Plate flowed through the juvenile Gangdese Batholith and ophiolites of Indus-Tsangpo Suture Zone, the melts would be modified by Gangdese Batholith and ophiolites, exhibiting characteristic Sr-Nd isotopes and geochemistry [18], but these adakitic rocks do not exhibit these features. Hence, the Himalayan lower crust was the most likely source for Himalayan Miocene adakitic rocks.

In summary, the Kuday granitoid porphyrite dikes are derived from partial melting of the thickened lower crust of the Himalayan Orogen.

6.2. Pervasive Miocene Magmatism in Southern Tibet. Widely distributed Miocene igneous rocks in southern Tibet include leucogranite, potassic/ultrapotassic rocks, and adakitic rocks [9–14, 26–29, 42, 43, 75, 80–82]. These contemporaneous magmatism events provided valuable but different insights to understand the tectonic evolution of southern Tibet. The temporal and spatial distribution of this Miocene magmatism indicates a similar tectonic setting in southern Tibet during the Miocene [75].

Miocene leucogranites are mainly exposed in the Himalayan Orogen and are commonly considered to be formed by anatexis of the metapelites and metagraywackes of the GHC with main age ranging from 12 to 26 Ma [9–14, 81, 82]. The occurrence of these leucogranites was generally attributed to the activity of the STDS and decompression partial melting [11, 83, 84]. Recently, researchers recognized the importance of mantle action in the formation of leucogranite in
Himalayan Orogen [85]. The contribution of the mantle to the formation of the leucogranite includes (1) upwelling of asthenosphere providing an additional heat source to the continued partial melting of the GHC [64, 86] and (2) causing significant N-S extension and the extrusion of the GHC, which induced or enhanced decompression melting of the GHC [87]. However, the discussions about the deep dynamic processes and mantle-derived heat promote the formation of the leucogranites are scarce in the Himalayan Orogen [13, 19].

The Miocene potassic and ultrapotassic rocks are mainly exposed in the Lhasa Terrane [46], and the Ramba lamprophyre dike is the only reported ultrapotassic rock within the Himalayan Orogen so far [73]. These K-rich rocks are characterized by low SiO₂ (<60 wt.% but high K₂O, enriched in the LILE, depleted in the HREE, and enriched radioactive Sr and Nd isotope (Figure 8), which were derived from metasomatized mantle source regions [41–43, 80]. The ages of the K-rich magmatism range from 25 to 8 Ma [46]. The consensus is that the upwelling of the asthenosphere is an important factor for partial melting of the metasomatized mantle [46, 73, 88].

Miocene adakitic rocks are exposed in both the Himalayan Orogen and the Lhasa Terrane, and a tremendous amount of work has been done on the adakitic rocks of the Lhasa Terrane over the past two decades [26–29]. In contrast, the contemporaneous adakitic rocks in the Himalayan Orogen are sparsely studied.

The Miocene adakitic rocks in Himalayan Orogen occurred as dike or pluton. These rocks are found within tens of kilometers of the IYSZ, forming a belt parallel to the IYSZ (Figure 1(a)), including, from east to west, the Yardoi two-mica (ca. 20–17 Ma) [15–17], Gyangzé granite porphyry dike and Bendui two-mica pluton (ca. 17–11 Ma) [19], Kuday dike (ca. 11 Ma, this study), Lasa Pluton (ca. 16.5 Ma) [18], and Mayum pluton (18–16 Ma) [20]. The model that these adakitic rocks are predominantly melted from the lower crust of the Himalayan Orogen is widely accepted [15–20]. A subtle difference is that some of these adakitic rocks were considered to be mixed with mantle-derived juvenile magma [19, 20], while others were considered to be purely partial melting of the lower crust [18].

Although there are subtle differences between the Lhasa adakitic rocks and Himalayan adakitic rocks during the Miocene, both adakitic rocks were formed in a similar tectonic setting. The partial melting of the thickened lower crust requires sufficient additional heat, and the two adjacent blocks were simultaneously heated by the asthenospheric upwelling [19].

The presence of three magmatic events concentrated in the Miocene may be a result of a uniform tectonic setting, asthenospheric upwelling, which led to the partial melting at different depths [64]. The leucogranite represented partial melting of mid-lower crust metasedimentary rocks [9–14, 81, 82], and the adakitic rocks represented partial melting of lower crustal mafic rocks [26–29], and potassic/ultrapotassic rocks represented partial melting of the lithospheric mantle [46].

6.3. Geodynamic Interpretation and Significance. For adakitic rocks derived from the thickened crust, we should interpret the following two relevant issues: (1) did the lower crust reach a thickness that would enable the formation of adakite and (2) what was the heat source for the melting of lower crust [26]?

As early as the Eocene, the Himalayan Orogen was thickened to the extent that can form adakitic rocks [35–37]. Metamorphism and anatexis also record early crustal thickening and plateau rising [89]. The crust of the Himalayan Orogen continues to thicken with the collision of the Indian Plate and Eurasian Plate [90]. In addition, Miocene eclogites in the central Himalaya have been identified, and these eclogites were formed by the crustal thickening, indicating the extremely thick crust of the Himalayan Orogen during the Miocene [91]. Recent research showed that the eclogites in the Thongmon and Dinggye reached peak pressure at ca. 17 Ma and then were overprinted by granulite facies metamorphism [91, 92]. Experimental petrology showed that partial melting of eclogites result in adakitic rocks [23, 74], so these eclogites are potential sources of the Miocene adakitic rocks. These studies indicated that the Himalayan Orogen had thickened before the Miocene (Figure 11(a)).

Several tectonic models have been proposed to explain the additional heat that allows partial melting of the lower crust: (1) delamination of the lithospheric mantle [18, 26, 27], (2) slab-tearing of the Indian Plate [49], and (3) rollback of the Indian Plate [48].

Geophysical data indicate that the present-day Himalayan lithosphere has undergone significant thinning [93]; the degree of thinning observed exceeds the extension observed at the surface [94]. Therefore, there would have to be foundering of the Himalayan lithosphere to explain this anomalous thinning [93]. For the Himalayan Orogen in particular, collisional processes would thicken rather than thin the lithospheric mantle, and thus, this thinning implies that part of the lithosphere has been delaminated into the mantle. In addition, P and S wave velocity models show a low-velocity anomaly down to ~300 km depth beneath the eastern Himalayan, which was thought to be a delaminated Indian lithosphere [95], and this provided powerful evidence for the delamination model. Furthermore, receiver-function profiles revealed that the subducted Indian slab changes from underplating to steep subduction in the India-Tibet collision zone [96], which indicates that the subducted Indian slab has been torn [97]. Therefore, we proposed that localized delamination of Himalayan lithosphere and slab-tearing of the Indian plate synchronously contributed to asthenospheric upwelling and the formation of the adakitic rocks, and the delamination model played a major role in asthenospheric upwelling and lithospheric thinning.

In addition to the pervasive Miocene magmatism mentioned in the above discussion, the delamination model can provide excellent explanations for the tectonic phenomena in southern Tibet during the Miocene (Figure 11(b)). The elevation of the Himalayan Orogen rapidly uplifts [6, 7, 90], which is consistent with the result of gravitational equilibrium after delamination [98]. The anomalously high
Figure 11: Cartoon model reveals the tectonic transition, geodynamic process, and the origin of adakitic rocks. (a) Prior to the Miocene, the Himalayan Orogen crust thickened because of the continued convergence of Asian and Indian plates. (b) The delamination of the lithospheric mantle, crustal thinning, and upwelling of the asthenosphere led to partial melting of the thickened lower crust and tectonic transition. The model was modified from Li et al. [18] and Lin et al. [20]. AFC: assimilation and fractional crystallization; GCT: Great Counter Thrust; GHC: Great Himalayan Crystalline Complex; IYSZ: Indus-Tsangpo Suture Zone; LHS: Lesser Himalayan Sequence; MBT: Main Boundary Thrust; MCT: Main Center Thrust; NHGD: North Himalayan Gneiss Dome; MHT: Main Himalaya Thrust; THS: Tethyan Himalayan Sequence; Si: Siwalik Group; STDS: South Tibet Detachment System.
metamorphic temperature was identified in the GHC, but previous studies often attributed it to frictional heating of STDS or MCT rapid movement [99]. Recent studies show that the GHC experienced ultra-high-temperature metamorphism during the Miocene, and the maximum temperature reached at 900–970°C [100]. Wang et al. [100] concluded that thinning of the lithosphere to <90 km was an important factor in the ultra-high-temperature metamorphism. Similarly, the records of high-temperature metamorphic rocks are also found in the Namche Barwa Syntaxis and the Nanga Parbat Syntaxis [101, 102]. The formation of the NSRT in southern Tibet is also related to the lithosphere thinning and the asthenospheric upwelling. The delamination model provides a reasonable explanation for the formation of the NRST [93].

In conclusion, the delamination model with the lithosphere thinning and the asthenospheric upwelling provides a reliable mechanism for the explosive appearance of various magmatism, high-temperature metamorphism, coupling of surface structure and deep geodynamic process, and plateau uplift in southern Tibet during the Miocene.

7. Conclusion

(1) The Kuday adakitic rocks originated from partial melting of the thickened lower crust of the Himalayan Orogen
(2) Eruptive occurrence of massive magmatism in southern Tibet during the Miocene may be a result of a uniform tectonic setting
(3) The delamination of the Himalayan lithospheric mantle led to the formation of the adakitic rocks and tectonic transition in the Himalayan Orogen during the Miocene

Data Availability

All Whole-rock geochemistry data, Sr-Nd isotope data and zircon U-Pb dating data support the findings of this study are included within the supplementary information files.

Conflicts of Interest

The authors declare that we have no known competing financial and personal relationships with people or organizations that can inappropriately influence our work.

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Supplementary Materials

Table S1: zircon U-Pb dating results of the Kuday adakitic rocks. Table S2: whole-rock geochemistry of the Kuday adakitic rocks. Table S3: Sr-Nd isotopic data of the Kuday adakitic rocks. (Supplementary Materials)

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