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Citation for final published version:

Xu, Chuan-Bing, Wang, Jun, Wang, Qiang, Kerr, Andrew C. , Li, Wu-Fu, Liu, Jin-Heng, Wang, Bing-Zhang, Li, Shan-Ping, Wang, Chun-Tao, Wang, Zi-Long and Gong, Lin 2024. First identification of Mid-Miocene north-south trending dikes in the eastern Qiangtang terrane, eastern Tibet: Mantle melting and implications for plateau uplift. *Lithos* 478-9 , 107620. 10.1016/j.lithos.2024.107620

Publishers page: <http://dx.doi.org/10.1016/j.lithos.2024.107620>

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2 **First identification of Mid-Miocene north–south trending dikes in the eastern**
3 **Qiangtang terrane, eastern Tibet: Mantle melting and implications for plateau**
4 **uplift**

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Abstract

The uplift of the Tibetan Plateau during the Miocene is crucial to understanding continental deformation processes and global climatic events. However, the eastern Tibetan Plateau remains poorly investigated. Mantle-derived magmatism provides crucial insights into the deep dynamic processes and surface uplift of the plateau. In this paper we report the first discovery of north–south trending lamprophyre dikes from the Aduo Basin in the eastern Qiangtang terrane, eastern Tibet. Our new age data show that these lamprophyre dikes were generated in Mid-Miocene (15–13 Ma). This new discovery has bridged the Mid-Miocene mantle-derived magmatic gap in the Qiangtang terrane. Trace element and Nd–Sr isotopic data indicate that they were derived by partial melting of enriched subcontinental lithospheric mantle. Our study implies that the eastern Tibetan Plateau had its attained near-maximum elevation by the Mid-Miocene. Combined with previous research results, we propose that the entire plateau almost simultaneously reached its near-maximum elevation by the Mid-Miocene.

Key words: north–south trending dikes; Miocene; east–west extension; Qiangtang; Tibetan Plateau

1. Introduction

The Tibetan Plateau is the youngest and highest plateau on Earth, and The surface uplift history of the Tibetan Plateau is crucial for understanding continental deformation processes and global climatic events (Deng and Ding, 2015; Ding et al., 2022). The Miocene epoch is now deemed critical for understanding the timing of the attainment of the highest paleoelevation of the Tibet (Coleman and Hodges, 1995; Spicer et al., 2003; Ding et al., 2022; Miao et al., 2022). However, compared with the abundant proxy data and paleoelevation reconstructions for southern, central and northern Tibet (Coleman and Hodges, 1995; Blisniuk et al., 2001; Spicer et al., 2003; Rowley et al., 2006; Deng and Ding, 2015; Miao et al., 2022; Li and Garzzone, 2023), the eastern part—despite being an integral part of the Tibetan Plateau—remains poorly understood.

In eastern Tibet (east of 94°E), it is suggested that the surface has been elevated above sea level since the closure of Paleotethyan ocean during the late Triassic to Jurassic period (Kapp and DeCelles, 2019). Additionally, the presence of adakitic rocks and dikes within the Qiangtang terrane indicates the onset of surface uplift during the early to middle Eocene (Wang et al., 2008a, b; Wang et al., 2010; Ou et al., 2017; Zhang et al., 2020). Structural analyses suggest that post-late Eocene tectonic shortening has occurred in this region, contributing to the uplift (Spurlin et al., 2005). Recent paleoaltimetric studies reveal that eastern Tibet did not achieve significant elevational heights during the Eocene, with an additional increase of 1.1–1.2 km in

elevation, to reach present levels, occurring after the late Eocene (Li et al., 2019). As such, the timing and mechanisms through which eastern Tibet attained its near-present elevation remain unresolved.

Convective thinning of the lithosphere causes an increase in the geothermal gradient and thus induced potassic melt generation via small-degree melting of remnant lithospheric mantle if it had been previously enriched (Turner et al., 1993; Chung et al., 1998). Therefore, surface uplift, extension and lithospheric-mantle-derived potassic magmatism (e.g., N–S trending dikes) may all be reconciled with thinning of the lithospheric mantle (Williams et al., 2001). The onset of E–W extension was recorded by N–S trending dikes represents the time when the near-maximum elevation of the plateau had been reached (England and Houseman, 1989; Harrison et al., 1995; Blisniuk et al., 2001; Williams et al., 2001).

This study reports the first geochronological and geochemical data of newly discovered north–south trending lamprophyre dikes from the Aduo Basin in the north of the Tanggula Mountains, eastern Qiangtang terrane, eastern Tibet. The discovery of lamprophyres has bridged the Mid-Miocene mantle-derived magmatic gap (26–8 Ma) in the Qiangtang terrane (Zhang et al., 2022). The dikes therefore provide qualitative constraints for the study of the plateau uplift during the Miocene, and also provide a medium for the exploration of the deep dynamic processes related to plateau uplift.

2. Geological setting

The Tibetan Plateau consists of five main blocks from north to south; that is, the Kunlun–Qaidam, Songpan–Ganzi, Qiangtang, Lhasa, and Himalaya terranes, which are separated by four main sutures (e.g., [Yin and Harrison, 2000](#); [Chung et al., 2005](#)). The Qiangtang terrane is located in the central part of the Tibetan Plateau, and it has been divided into the North and South Qiangtang terranes based on the Longmu Co–Shuanghu Suture Zone ([Li et al., 1995](#); [Zhu et al., 2013](#); [Zhang et al., 2016](#)). The North Qiangtang terrane is separated from the Songpan–Garzi and South Qiangtang terranes by the Jinshajiang and Longmu Co–Shuanghu suture zones, respectively ([Zhai et al., 2013](#)). The South Qiangtang terrane records a complicated tectonic history as a result of the subduction of two Paleotethyan oceans and collision of three terranes ([Yang et al., 2014](#); [Zhang et al., 2020](#)). There were two Permian–Triassic arc-like volcanic belts on the North Qiangtang terrane ([Yang et al., 2011](#); [Yang et al., 2012](#); [Zhai et al., 2013](#); [Li et al., 2019](#); [Zhang et al., 2020](#)). The earlier one was formed in ca. 275–236 Ma, and it consists of silicic rocks and associated volcanoclastics ([Yang et al., 2011](#); [Zhang et al., 2013](#)). This belt is interpreted to be formed by the northward subduction of the Paleotethyan ocean along the Longmu Co–Shuanghu suture ([Li et al., 2019](#); [Zhang et al., 2020](#)). The later arc-like volcanic belt consists of Late Triassic (225–200 Ma) mafic to felsic rocks and volcanoclastics that resulted from the southward subduction of the Jinshajiang ocean ([Yang et al., 2012](#); [Zhang et al., 2020](#)). The final amalgamation of the Songpan–Ganzi, North Qiangtang, and South Qiangtang terranes was completed in the Early Jurassic ([Yin](#)

and Harrison, 2000; Yang et al., 2012; Zhai et al., 2013), and since then, the North Qiangtang area has been in an intra-continental setting.

The Cenozoic Indo-Eurasia collision produced considerable crustal shortening within the plateau (Yin and Horrison, 2000; Li et al., 2012, 2015). The main thrust systems in the North Qiangtang terrane include the Tanggula thrust system (TTS), the Fenghuoshan (FTS) and Nangqian thrust belt (NTB) (Li et al., 2015). These thrust belts occurred between the Late Cretaceous and Early Miocene (23 Ma), and resulted in a total of 200 km crustal shortening (Li et al., 2015). The thrust systems dominated the development of the Cenozoic basin, and resulted in the rapid uplift of the Tanggula Shan during the Eocene–Oligocene (Li et al., 2015).

Cenozoic magmatic rocks are widespread in the Qiangtang terrane (Ding et al., 2003; Chung et al., 2005; Wang et al., 2008b, 2016; Guo and Wilson, 2019), and they were formed during two magmatic episodes at 51–26, and 8–2.3 Ma, with a magmatic flare-up in the Eocene. The Eocene magmatic rocks were predominantly adakitic, alkalic and shoshonitic lavas (Ding et al., 2003; Wang et al., 2008b, 2010; Chen et al., 2018; Guo and Wilson, 2019). Minor 6.0–2.3 Ma felsic volcanic lavas derived by crustal melting have recently been found in the Dongyue Lake, Henglianghu and Chibuzhangcuo regions (Wang et al., 2016), In addition, Zhang et al. (2022) recently reported ~9.0 Ma granite xenoliths in Pliocene lavas. Some Miocene mantle-derived potassic-ultrapotassic magmatic rocks in the Qiangtang terranes in central Tibet have

also once been reported in some references (Turner et al., 1993, 1996; Williams et al., 2004). However, more detailed geological investigations (e.g., Guo et al., 2006; Wang et al., 2008, 2010, 2016; Qi et al., 2023) suggest that, except for Eocene-Oligocene mantle-derived rocks, no Miocene mantle-derived potassic-ultrapotassic magmatic rocks occur in the Qiangtang terrane.

3. Field occurrence and petrography

The Aduo Basin is situated in the north of the Tanggula Mountains, eastern Qiangtang terrane, eastern Tibet (Fig. 1a). The Aduo dikes investigated in this study are located in the Aduo Basin, a region east of the Zaduo County, southern Qinghai Province. In this area there are some outcrops of Carboniferous to Neogene sedimentary and volcanic rocks, cut by several NE–SW and NW–SE trending reverse faults (Fig. 1b). These reverse faults belong to part of the Fenghuoshan–Nangqian thrust belt system (Spurlin et al., 2005; Li et al., 2012). The lamprophyre dikes consist of four undeformed subparallel dikes with the thickness of 0.5–4 m (Fig. 2a, b). The lamprophyre dikes, with NS–striking orientations (Fig. 2a, b), intruded the Neogene clastic rocks (Fig. 2a-b).

Samples were collected from the center of four dikes. The GPS coordinates of the points where the samples were collected are 32°53'3.6"N, 94°41'7"E and 32°53'2.6"N, 94°41'4.8"E. All samples are dark grey and display porphyritic texture (Fig. 2c, d). The rocks are mainly composed of phlogopite, diopside and sanidine.

Accessory minerals are apatite, zircon and magnetite. Phenocrysts include euhedral laths of zoned phlogopite and diopside (Fig. 2d, f). The groundmass consists of poikilitic phlogopite, interstitial sanidine and microcrystalline diopside (Fig. 2c, d, e, f). $^{40}\text{Ar}/^{39}\text{Ar}$ dating on fresh phlogopite phenocrysts was carried out on five samples. Major and trace element analyses were determined for all samples, while Sr–Nd isotopic analyses were obtained from six representative lamprophyre samples.

4. Analytical methods

4.1. Mineral composition analyses

Major element compositions and back-scattered-electron imaging for minerals were carried out at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (SKLaBIG GIG-CAS) by using a JXA-8100 electron microprobe. An accelerating voltage of 15 kV, a specimen current of 3.0×10^{-8} A, and a beam size of 1 μm were employed. Analytical errors are generally less than 2%. The detailed analytical procedure is given in Huang et al. (2007).

4.2. Phlogopite $^{40}\text{Ar}/^{39}\text{Ar}$ dating

The phlogopite samples were washed repeatedly in a centrifuge tube using acetone and deionized water. Samples packed in aluminum foil were placed into quartz tubes, and the discs were then Cdshielded and irradiated in a reactor for 21 h. $^{40}\text{Ar}/^{39}\text{Ar}$ laser stepwise heating experiments were conducted at the SKLaBIG

GIG-CAS. $^{40}\text{Ar}/^{39}\text{Ar}$ dating was performed using a GV5400 Ar–Ar mass spectrometer. Details of the experimental procedure can be found in [Qiu and Jiang \(2007\)](#). The raw data were processed using ArArCALC software (version 2.4; [Koppers, 2002](#)), and the ages were calculated using the decay constants recommended by [Renne et al. \(2010\)](#). Age uncertainties include all sources of errors and were calculated following [Renne et al. \(2010\)](#).

4.3. Whole-rock geochemical and Sr–Nd isotopic compositions

Fresh samples were used for geochemical analyses. The rocks were sawn into small chips, cleaned ultrasonically in distilled water with <3% HNO_3 (immersion time around 10 s) then in distilled water alone, and subsequently dried and handpicked to remove visible contamination. The rocks were then crushed and ground in a tungsten carbide ring mill, and each batch was subjected to three 1 min milling intervals (total milling time of around 3 min). The powders resulting from the milling were used for analyses of major- and trace-element contents and Sr–Nd isotopic compositions at the GIG-CAS. Major-element oxides were analyzed on fused glass beads using a Rigaku RIX 2000 X-ray fluorescence spectrometer at the SKLaBIG GIG-CAS. Calibration lines used in quantification were produced by bivariate regression of data from 36 reference materials encompassing a wide range of silicate compositions. Analytical results for United States Geological Survey (USGS) reference standards GSR-1, GSR-2, and GSR-3 showed that the analytical uncertainties are generally less than 2%. Trace elements, including rare earth elements (REEs), were analyzed using a Perkin–

Elmer Sciex ELAN 6000 ICP–MS instrument. The analytical procedures were similar to those described by [Li et al. \(2006\)](#). USGS reference standards BHVO-2, GSR-1, GSR-2, GSR-3, AVG-2, W-2, and SARM-4 were chosen for calibration. The analytical accuracy and precision for trace-element contents are better than 3%.

The Sr and Nd isotopic analyses were performed using a Micromass Isoprobe MC-ICP-MS instrument at the SKLaBIG GIG-CAS. Analytical procedures have been described by [Li et al. \(2006\)](#). Measured $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ and $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$, respectively. The reported $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were adjusted with respect to National Institute of Standards and Technology Standard Reference Material 987 ($^{87}\text{Sr}/^{86}\text{Sr} = 0.71025$) and Shin Etsu JNdi-1 ($^{143}\text{Nd}/^{144}\text{Nd} = 0.512115$), respectively.

5. Results

5.1. Mineral compositions

Representative major element compositions of phlogopite, clinopyroxene, sanidine and apatite are given in [Supplementary Table S1–S4](#), respectively.

Clinopyroxene ranges in composition from augite to aegirine ([Supplementary Table S1](#)). Most of the clinopyroxene is aegirine–augite and exhibits zoning with Mg-rich cores and Fe- and Na-rich rims. A few pure aegirines have also been identified in the Aduo lamprophyres ([Fig. 2e](#)).

The mica minerals from the Aduo lamprophyres are phlogopites on the basis of

their high Mg# (up to 94) and low Al contents ($\text{Al}_2\text{O}_3 = 10.9\text{--}15.2$ wt.%). Their TiO_2 contents are 1.2–3.5 wt.% (Supplementary Table S2).

Sanidine is another common K-rich phase that occurs as microcrystals in the groundmass (Fig. 2e, f). The analyzed sanidines have compositions in the range of $\text{Or}_{93\text{--}94}\text{Ab}_{6\text{--}7}$ (Supplementary Table S3).

Apatites are found as euhedral to subhedral crystals and with homogeneous textures in BSE images, indicating that no post-magmatic alteration occurred (Fig. 2e). The apatite contains 49.8 to 54.9 wt.% CaO , and 38.5 to 41.6 wt.% P_2O_5 (Supplementary Table S4).

5.2. Phlogopite Ar–Ar results

$^{40}\text{Ar}/^{39}\text{Ar}$ data for phlogopite phenocrysts (samples 19AD22-1, 19AD22-5, 19AD22-6, 19AD23-1, and 19AD23-4) from the Aduo lamprophyre dikes are presented in Supplementary Table S5 and shown in Fig. 3. The samples yield plateau ages of 13.02 ± 0.22 , 15.66 ± 0.55 , 13.83 ± 0.34 , 14.80 ± 0.29 , and 13.90 ± 0.35 Ma, respectively. The corresponding normal isochron ages for these plateaus are 12.56 ± 0.51 Ma (MSWD = 0.51), 14.79 ± 0.78 Ma (MSWD = 1.30), 13.50 ± 0.48 Ma (MSWD = 0.78), 13.68 ± 0.50 Ma (MSWD = 0.21), and 13.54 ± 0.66 Ma (MSWD = 0.08), respectively, which are consistent within errors with the plateau ages. The dating results show that all dike samples were formed in the Mid-Miocene (15–13 Ma).

5.3. Whole-rock geochemistry

All major, trace element and Sr–Nd isotopic compositions are provided in [Supplementary Table S6](#). The lamprophyres are mafic to intermediate with SiO₂ contents of 43.6–52.2 wt.% and are characterized by moderate-to-high MgO (6.6–11.5 wt.%) and high K₂O (6.3–7.7 wt.%). They have elevated Mg# [molar MgO/(molar MgO + molar FeOT) × 100] of 69–77 and K₂O/Na₂O > 2 (wt.%), and so display typical ultrapotassic characteristics ([Foley et al., 1987](#)). The lamprophyres have relatively low contents of Na₂O (0.5–1.3 wt.%), TiO₂ (0.8–1.1 wt.%), Fe₂O₃T (5.6–6.9 wt.%) and Al₂O₃ (8.7–10.8 wt.%).

The Aduo lamprophyres generally show subparallel chondrite-normalized rare earth elements (REE) and trace element patterns ([Fig. 4](#)). All the lamprophyres are enriched in the large ion lithophile elements (LILEs, e.g., Rb, Ba and K), and depleted in the high field strength elements (HFSEs, e.g., Nb, Ta and Ti) ([Fig. 4a](#)). Chondrite-normalized REE patterns show an enrichment in light REE (LREE) relative to heavy REE (HREE) ([Fig. 4b](#)). The lamprophyres have markedly enriched Sr–Nd isotopic compositions ([Fig. 5](#)), with highly radiogenic ⁸⁷Sr/⁸⁶Sr ratios of 0.7114–0.7122 and low ε_{Nd}(0) values of –9.6 to –11.5. The corresponding Nd model ages (T_{DM}) range from 1.9 Ga to 1.5 Ga.

6. Discussion

6.1. Alteration and crustal contamination

The lamprophyre samples have variable LOI (loss on ignition) values (6.2–9.3 wt.%). These are similar to the variable LOI reflecting variable H₂O, sulfur, halogen, and CO₂ contents from worldwide lamprophyre occurrences (Rock, 1987; Soder et al. 2016; Krmíek et al. 2020; Shen et al. 2022). Deuteritic alteration, which represents textural and mineralogical changes caused by exsolved magmatic hydrothermal fluids during the final crystallization stages of magmas, are ubiquitous in lamprophyric dike rocks (Rock, 1991). Since there is little involvement of external hydrothermal fluids, deuteritic alteration typically has minimal impact on the whole-rock compositions. The major elements (especially K₂O and Na₂O) and large-ion lithophile elements (LILEs) (e.g., Rb, Ba, Th) concentrations of all samples show no obvious correlation with LOI (Fig. 6a-f), suggesting minimal modification of these elements due to deuteritic alteration. The REEs, high-field strength elements (HFSEs) and compatible elements (Cr, Ni) are insoluble and thus remain essentially immobile during intensive alteration (Polat and Hofmann, 2003). Additionally, $\epsilon_{\text{Nd}}(0)$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values do not correlate with LOI (Fig. 6g-h), indicating that they were also unaffected by subsequent post-magmatic alteration. Therefore, the major and trace elements within lamprophyres were essentially immobile during deuteritic alteration.

The Aduo lamprophyres have relatively high MgO (6.6–11.5 wt.%), Cr (348–587 ppm), Ni (271–454 ppm) contents and Mg# (69–77) which characterize mantle-derived primary lamprophyre magmas (Mg# = 65–80, Sc = 15–30 ppm, Cr = 200–500 ppm, Co = 25–80 ppm and Ni = 90–700 ppm; Rock, 1991). Their primitive major and trace element characteristics also rule out a significant role for crustal

contamination and fractional crystallization. Moreover, their extreme enrichment in incompatible elements make them insensitive to crustal contamination. The samples show consistent trace element and REE patterns (Fig. 4a, b), and the extreme enrichment of LREE and absence of significant Eu anomalies (Fig. 4b) also imply that the magma did not undergo significant crustal contamination. Thus, the effect of crustal contamination on magma evolution of the Aduo lamprophyres is probably very limited. Previous studies have also suggested that crustal assimilation did not play a significant role in the petrogenesis of the mafic dikes in the Tibet (Williams et al., 2001; Wang et al., 2010).

6.2. Petrogenesis of the Aduo lamprophyres

The Aduo lamprophyres have high abundances of incompatible trace elements, clearly suggesting the derivation of magmas from an enriched mantle source (Soder et al. 2016; Krmíek et al. 2020). Given the insignificant role of crustal contamination, the high degrees of incompatible element enrichment, and the extremely high $^{87}\text{Sr}/^{86}\text{Sr}$ and low $\epsilon_{\text{Nd}}(0)$ values isotopic compositions, indicate that the lamprophyres originated from metasomatized subcontinental lithospheric mantle, rather than from asthenosphere mantle (Hofmann, 1988). The Aduo lamprophyres are characterized by significant depletions in Nb, Ta, Ti, and Zr and marked enrichments in incompatible elements including Rb, Ba, Th, U, K, and LREEs on primitive mantle-normalized diagrams (Fig. 4). The negative anomalies in Nb, Ta, and Ti in the Cenozoic K-rich rocks in Qiangtang terrane, indicate that the subduction processes were probably

responsible for the metasomatism of their continental mantle source region (Thirlwall et al., 1994; Miller et al., 1999; Turner et al., 1993, 1996).

Mantle metasomatism by subduction may occur during intracontinental subduction in the Cenozoic or earlier oceanic subduction in the Mesozoic (Qi et al., 2023). In this section we first discuss the Mesozoic lithospheric-mantle-derived mafic rocks in the eastern Qiangtang terrane (Yang et al., 2012; Ma et al., 2021; Ou et al., 2021) in order to constrain the nature of Mesozoic lithospheric mantle. They have depleted Sr–Nd isotopes relative to Cenozoic mantle-derived rocks ($\text{MgO} > 6 \text{ wt.}\%$) in the eastern Qiangtang terrane (Fig. 5). These characteristics imply that the enriched lithospheric mantle sources of Cenozoic mantle-derived rocks in the eastern Qiangtang terrane were formed after the Mesozoic. The Aduo lamprophyres have $\epsilon_{\text{Nd}}(0)$ values (-11.5 to -9.6) that overlap 51–26 Ma mantle-derived rocks in the eastern Qiangtang terrane and they plot in the field of Sr–Nd isotopic compositions for the Songpan–Ganzi sediments (Fig. 5; She et al., 2006; Deschamps et al., 2017). Therefore, we infer that subducted Songpan–Ganzi terrane was the agent of lithospheric mantle enrichment beneath the eastern Qiangtang terrane.

Plank, (2005) proposed that high Th/La ratios in arc magmas inherit their Th/La from subducting sediment. The Aduo lamprophyres have relatively high Th (27.1–33.1 ppm) content and Th/La ratios (0.19–0.30, Fig. 7) suggesting that the Th-enriched sedimentary component in the lamprophyres source was probably

introduced via partial melting of subducted sediments (Plank, 2005; Gao et al., 2007). Experimental results also indicate that Th enrichment in a subduction zone requires melting of sediments (Johnson and Plank, 2000), especially clay-rich mature sediment or mudstone (Zou et al., 2014). The Proterozoic–Triassic sediments in the Songpan-Ganzi terrane, including the Triassic flysch, have Th/La values (Chen et al., 2006; She et al., 2006), which overlap with those of the Aduo lamprophyres (Fig. 7). Partial melts derived from subducted sediments have K₂O-rich, quartz-saturated compositions (Thomsen and Schmidt, 2008). These melts may rise into the mantle wedge and react with the peridotite, leading to the formation of phlogopite and orthopyroxene at the expense of olivine (Soder et al., 2016). We suggest that the evidence overwhelmingly supports an important role for the melting of subducted continental sediments in the metasomatic enrichment of lithospheric mantle in the Aduo area.

Chondrite-normalized REE patterns of the Aduo lamprophyres indicate significant enrichment in LREE, suggesting a low degree of partial melting (Fig. 4b). Partial melts of the garnet-facies mantle are characterized by high Dy/Yb ratios (>2.5), whereas melting in the spinel stability field would produce melts with lower Dy/Yb ratio (<1.5) (Duggen et al., 2005). The Aduo lamprophyres have Dy/Yb ratios ranging from 3.4 to 4.6, implying that partial melting took place in the garnet stability field. In summary, we propose that the Aduo lamprophyres were derived by the low-degree partial melting of garnet-facies lithospheric mantle previously enriched by subducted

sediment-derived K-rich melts.

5. Implications

5.1. Filling the Mid-Miocene magmatic gap in the Qiangtang terrane

Mafic magmatism is a response to processes occurring in the deep mantle. Cenozoic magmatic rocks are unevenly distributed in the Qiangtang terrane and are mainly concentrated in the northern part of the terrane (Wang et al., 2008b). They were generated between 51–26 Ma and 8.0–2.3 Ma (Spurlin et al., 2005; Wang et al., 2008b, 2010, 2016; Ou et al., 2017, 2019; Chen et al., 2018). The 51–26 Ma volcanic and intrusive rocks include mafic, intermediate and felsic rocks (Ding et al., 2003; Guo et al., 2006; Wang et al., 2008b, 2010; Lai and Qin, 2013; Long et al., 2015; Ou et al., 2017, 2019). The 8.0–2.3 Ma rocks are dominated by trachyandesites, dacites, and rhyolites and were produced by partial melting of a relatively hot and anhydrous middle-lower crust (Wang et al., 2016; Chen et al., 2018; Zhang et al., 2022). There is no mantle-derived magmatism in the Qiangtang terrane hinterland from 26 Ma to 8 Ma (Fig. 8). Therefore, the deep process below Qiangtang terrane in the Early to Mid-Miocene is unknown. Recent research shows that the middle–lower crust of the Qiangtang terrane became extremely hot and weak since the early Miocene, and the crustal melt largely failed to reach the surface and existed mainly as unexposed felsic plutons (Zhang et al., 2022). Combined with the petrogenesis of the Aduo lamprophyres (15–13 Ma), we suggest that removal of lower lithospheric mantle and concomitant upwelling of asthenospheric mantle most likely induced the high

geothermal gradient, and hence hot and weak crust.

5.2. Rise of the eastern Tibet in the Mid-Miocene

Oxygen and clumped isotope palaeoaltimetry analyses indicate that the Nangqian Basin, that is approximately 120 kilometers east of the Aduo Basin, achieved a mean elevation of approximately 3.0 km by around 37 Ma (Li et al., 2019). From the late Eocene to the present, this region experienced an uplift of 1.1 to 1.2 km to reach its current elevation (Li et al., 2019). Research by Xu et al. (2016) suggests that the eastern Tibetan Plateau had ascended to near-modern elevations by the late Miocene, indicating deep geodynamic processes occurring between the late Eocene and the late Miocene led to the uplift of eastern Tibet. Furthermore, the presence of extensive, yet undeformed lake basins, dating from approximately 24 to 14 Ma, scattered across northern and eastern Tibet, suggests that surface uplift was likely facilitated by either the inflow of buoyant lower crust (Wang et al., 2016), convective removal of mantle lithosphere (Molnar et al., 1993) or lithosphere delamination (Kelly et al., 2020), or a combination of these processes (Ding et al., 2022).

Numerical experiments suggest that convective removal of the lower part of thickened lithospheric mantle and its replacement by hot asthenosphere would lead to a rapid increase in the surface height (as much as 2 km) and gravitational potential energy of the upper part of the lithosphere (England and Houseman, 1989; Jiménez-Munt and Platt, 2006). This increase is sufficient for E–W extension to

replace N–S compression as the dominant feature of the stress field of the Tibetan plateau (England and Houseman, 1989). The latest research indicate that the Indian continental lithosphere is below the eastern Qiangtang terrane (van Hinsbergen, 2022; Xia et al., 2023), and northward advancing subduction of Indian lithosphere induced thickening and delamination of the weaker Asian lithosphere (Kelly et al., 2020). Our new $^{40}\text{Ar}/^{39}\text{Ar}$ ages show that Aduo lamprophyre dikes were emplaced at 15–13 Ma, Given that north–south trending dikes are unambiguous indicators of fracture propagation and extension (Williams et al., 2001; Garzione et al., 2003; Wang et al., 2010), our results suggest east–west extension in eastern Tibet occurred in the Mid-Miocene. If we accept the topographically driven model for the east–west extension in Tibet, then the extension as recorded by the Aduo north–south trending dikes implies that the eastern Tibetan Plateau had already attained near-maximum elevation in the Mid-Miocene.

The Miocene east–west extension was widely distributed in southern and central Tibet (Fig. 1a; Li et al., 2015 and references therein). The Aduo north–south trending lamprophyre dikes were emplaced at 15–13 Ma, suggesting east–west extension in eastern Tibet occurred in the Mid-Miocene. Correlations between Cenozoic paleo-altitude data (Fig. 9a) and the timing of east–west extension (Fig. 9b) across different sectors of the Tibetan Plateau suggest a concurrent development of the modern-like plateau and the initiation of east–west extension during the Mid-Miocene.

420

421 **6. Conclusions**

422 The geochronology and geochemistry of recently discovered lamprophyre dikes
423 from the Aduo Basin of the Qiangtang terrane, eastern Tibet have been used to
424 constrain the timing and deep dynamic processes of surface uplift of the Tibetan
425 Plateau. The main conclusions of our study are as follows.

426 (1) The phlogopite $^{40}\text{Ar}/^{39}\text{Ar}$ dating shows that the Aduo north–south trending
427 lamprophyre dikes were formed during the Mid-Miocene (15–13 Ma). The Aduo
428 lamprophyres were most likely derived from partial melting of enriched
429 subcontinental lithospheric mantle.

430 (2) The discovery of Aduo lamprophyres has filled the Mid-Miocene mantle-derived
431 magmatic gap in the Qiangtang terrane. The Aduo dikes imply that the eastern Tibetan
432 Plateau had already attained near-maximum elevation in the Mid-Miocene. Our new
433 data combined with previous research results, indicate that the entire plateau reached
434 its near- maximum elevation almost simultaneously by the Mid-Miocene.

435

436 **Acknowledgements**

437 Financial support for this research was provided by National Natural Science
438 Foundation of China (42021002) and the Second Tibetan Plateau Scientific
439 Expedition and Research (STEP) (2019QZKK0702). This is contribution No.
440 IS-XXX from GIGCAS.

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Figure captions

Fig. 1. (a) Tectonic and topographic map of the Himalayan-Tibetan with major structures (modified from [Fan et al., 2023](#)). Light green boxes—previous estimates for onset of E–W extension (units in Ma; numbers in parentheses indicate timing of accelerated footwall exhumation). (b) Simplified geologic map showing outcrops of volcanic rocks and north–south trending dikes in the the Aduo Basin.

Fig. 2. Field photographs, photomicrographs and back scattered electron (BSE) images depicting the overall petrographic aspects of the Aduo lamprophyre dikes. (a), (b) Field photographs of Aduo north–south trending lamprophyre dikes from different perspectives; (c) Photomicrographs of the lamprophyre, showing phenocrysts include euhedral laths of phlogopite and diopside. They are set in a groundmass of poikilitic phlogopite, interstitial sanidine and microcrystalline diopside (polarized); (d) Zoned clinopyroxene and phlogopite (BSE). (e) The cluster phenocrystals of phlogopite (polarized). (f) Photomicrographs of the lamprophyre (cross-polarized light). Phl: phlogopite; Cpx: clinopyroxene; San; sanidine; Apt: apatite; Aeg:aegirine. The dashed yellow lines depicted in the figure represent the dikes, and the dashed white lines represent the contact between the dikes and wall rock.

Fig. 3. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age plots for phlogopites of Aduo lamprophyre dikes.

Fig. 4. Primitive-mantle-normalized trace-element diagrams (a) and chondrite-normalized REE patterns (b) for the Aduo lamprophyres. Chondrite- and primitive-mantle-normalized values are from [Sun and McDonough \(1989\)](#). Miocene (ultra-) potassic rocks are from [Guo and Wilson \(2019\)](#), [Qi et al. \(2020\)](#).

Fig. 5. Whole-rock Nd–Sr isotope diagrams for the the Aduo lamprophyres. Data sources: pre-collisional mafic rocks: [Yang et al., 2012](#), [Ma et al. \(2021\)](#) and [Ou et al. \(2021\)](#). Crustal xenoliths: [Lai et al. \(2011\)](#). 51–26 Ma magmatic rocks: [Guo et al. \(2006\)](#), [Wang et al. \(2008b, 2010\)](#), [Guo and Wilson \(2019\)](#), [Ou et al. \(2019\)](#), and [Qi et al. \(2023\)](#). 8.0–2.3 Ma felsic rocks: [Wang et al. \(2016\)](#) and [Chen et al. \(2018\)](#).

Fig. 6. Plots of loss on ignition (LOI) in wt.% versus major, trace elements and Sr–Nd isotopic compositions for the the Aduo lamprophyres.

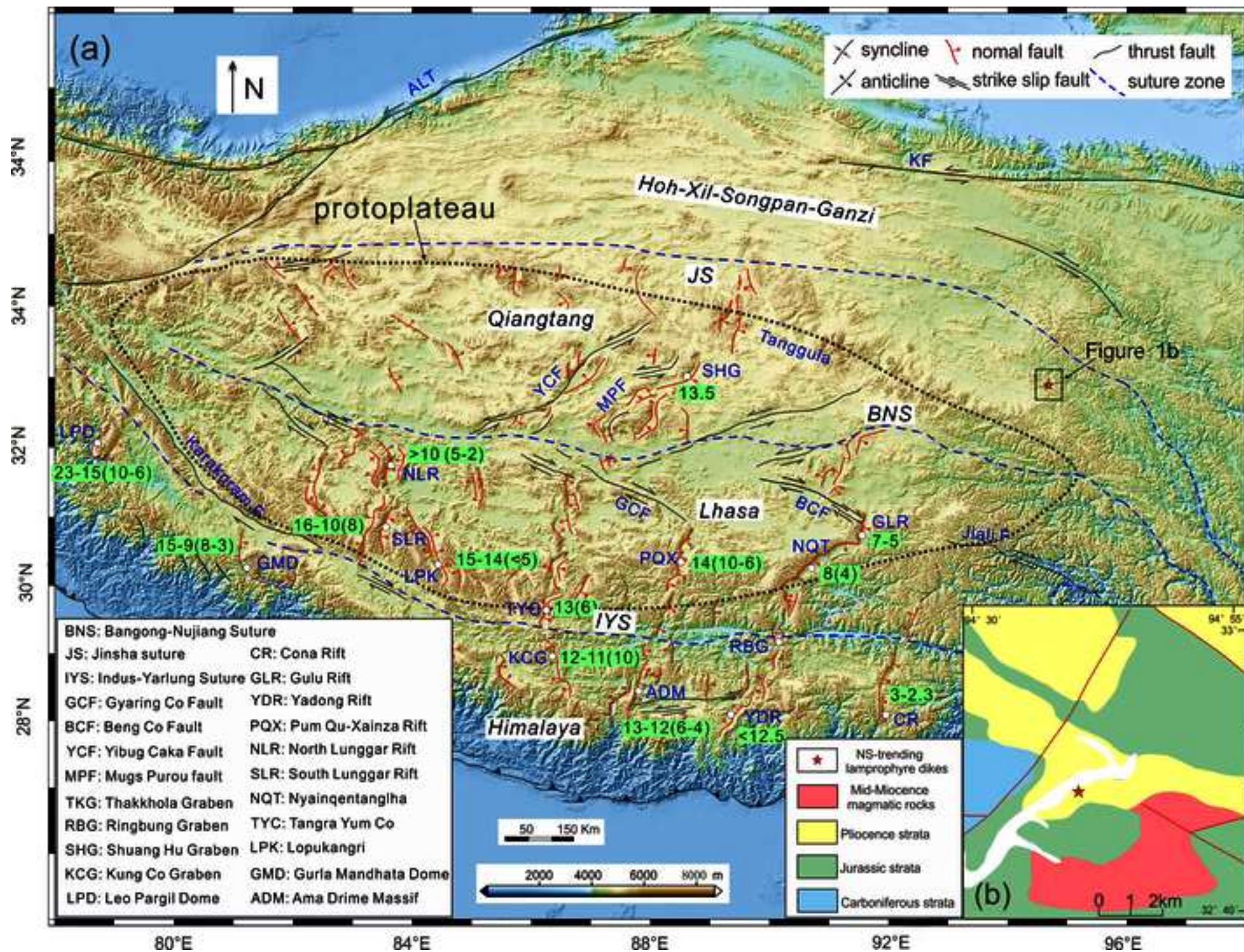
Fig. 7. Diagram of Th/La vs Sm/La. Fields of MORB, OIB and Average GLOSS are from [Plank. \(2005\)](#) and references therein.

Fig. 8. Age histogram diagram for Cenozoic magmatic rocks of the Qiangtang terrane (bin width is 3.5 Ma). Cenozoic magmatic rock data are from [Chung et al. \(2005\)](#), [Wang et al. \(2016\)](#), and [Guo and Wilson \(2019\)](#).

Fig. 9. History of surface elevation change across Tibet (a) and age distribution of major Cenozoic E–W extensional structures (b). The paleo-altitude data are from [Nie et al. \(2020\)](#), [Ding et al.](#)

734 (2022) and Li and Garzione (2023). The age data for E–W extensional structures are from Li
735 et al. (2015) and Fang et al. (2023).
736

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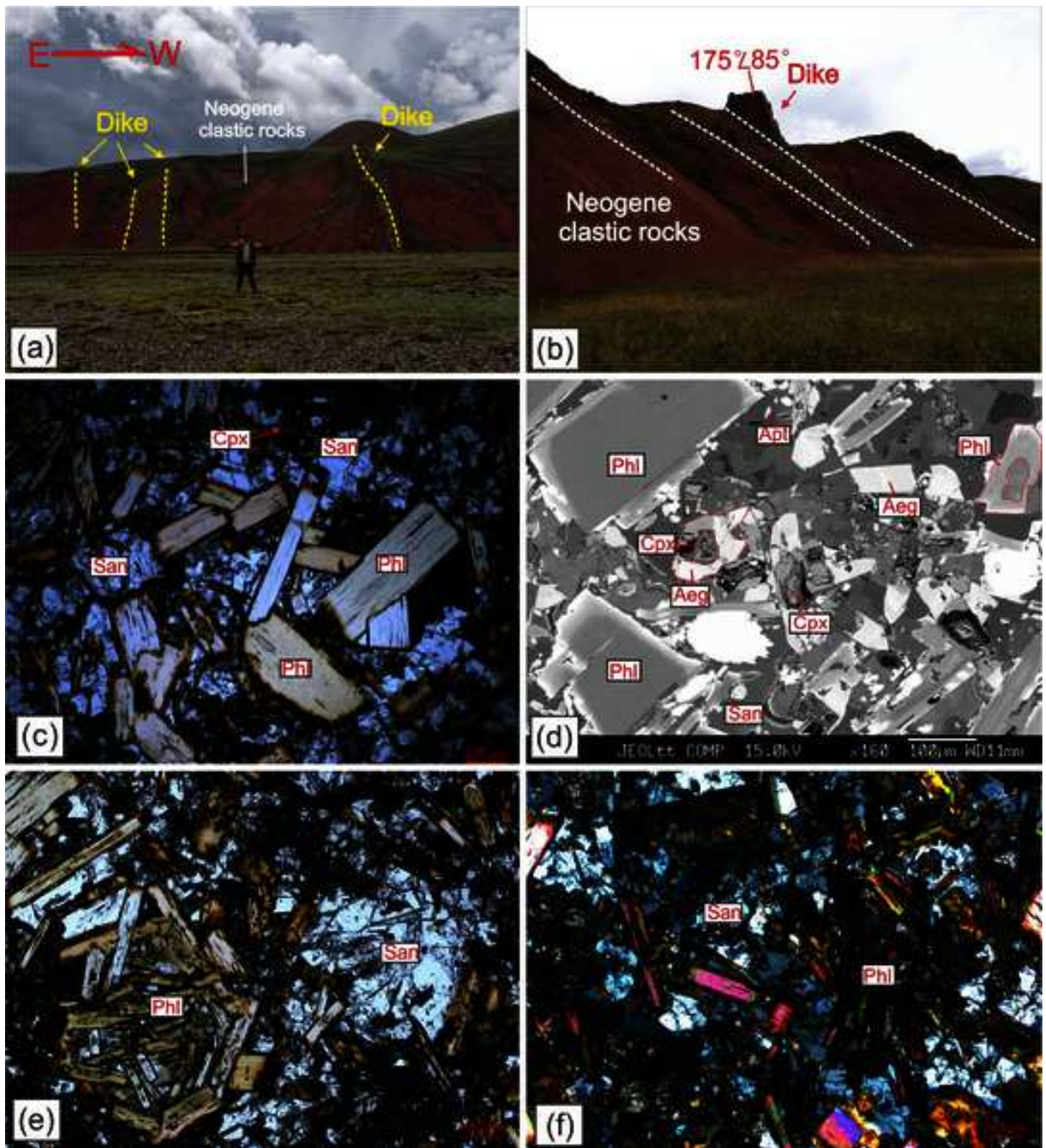


Figure 3

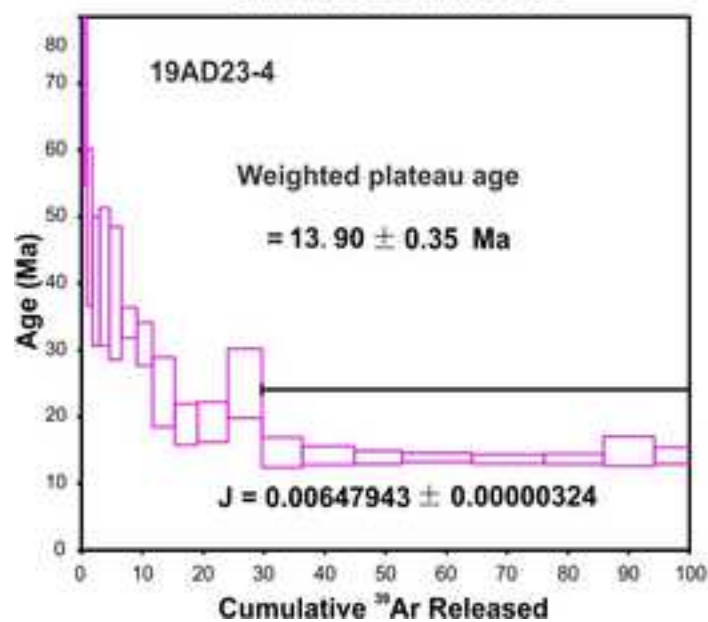
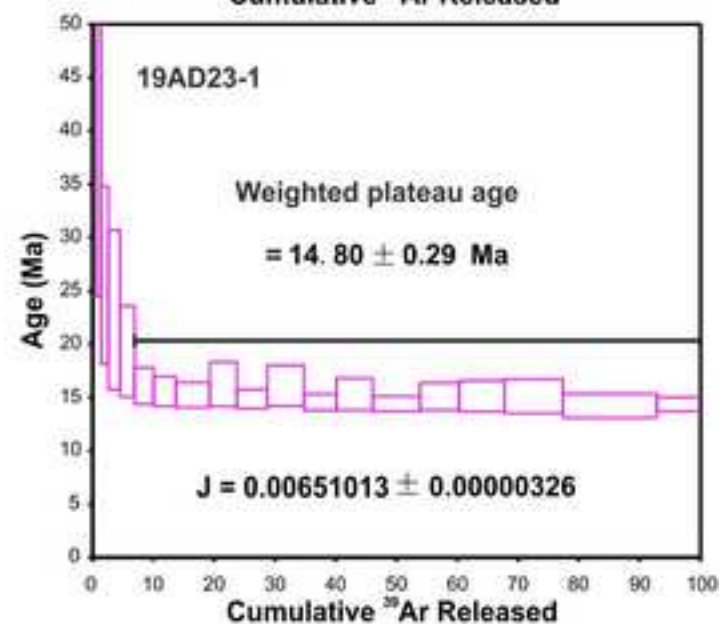
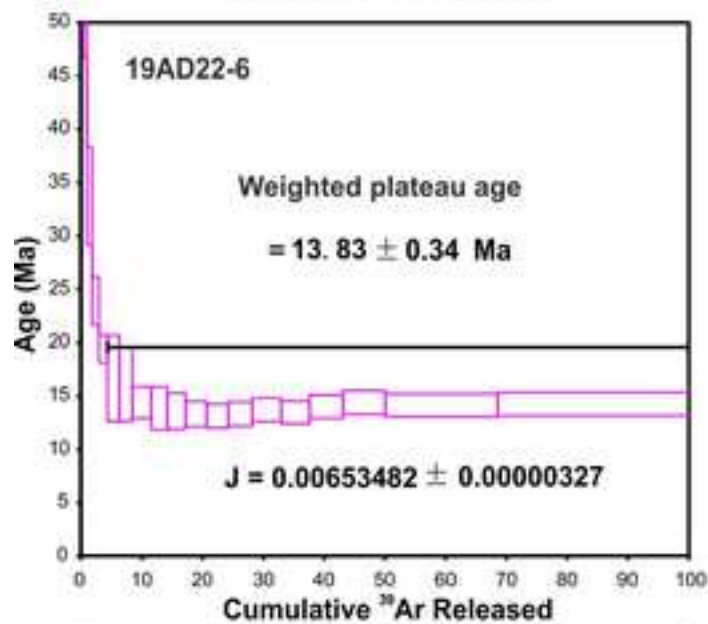
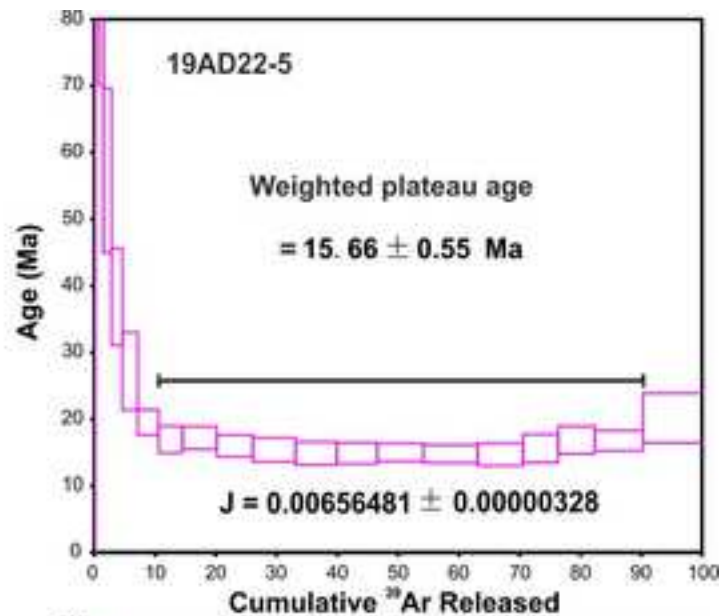
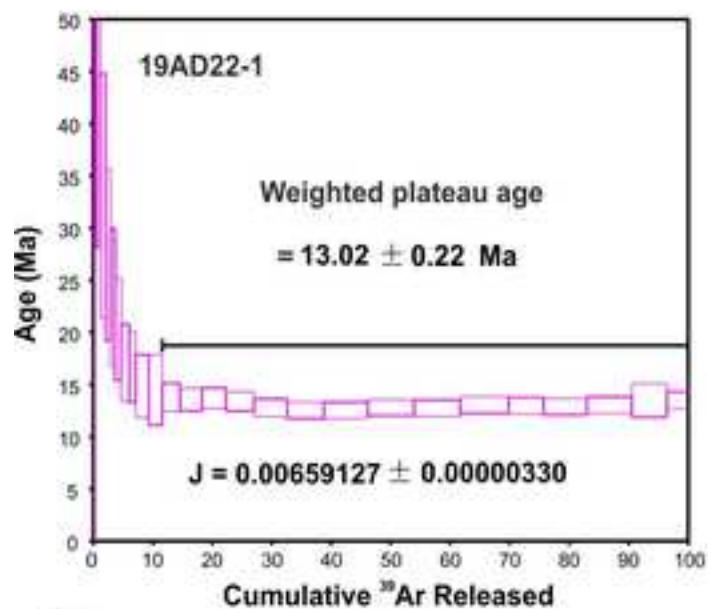
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Figure 4

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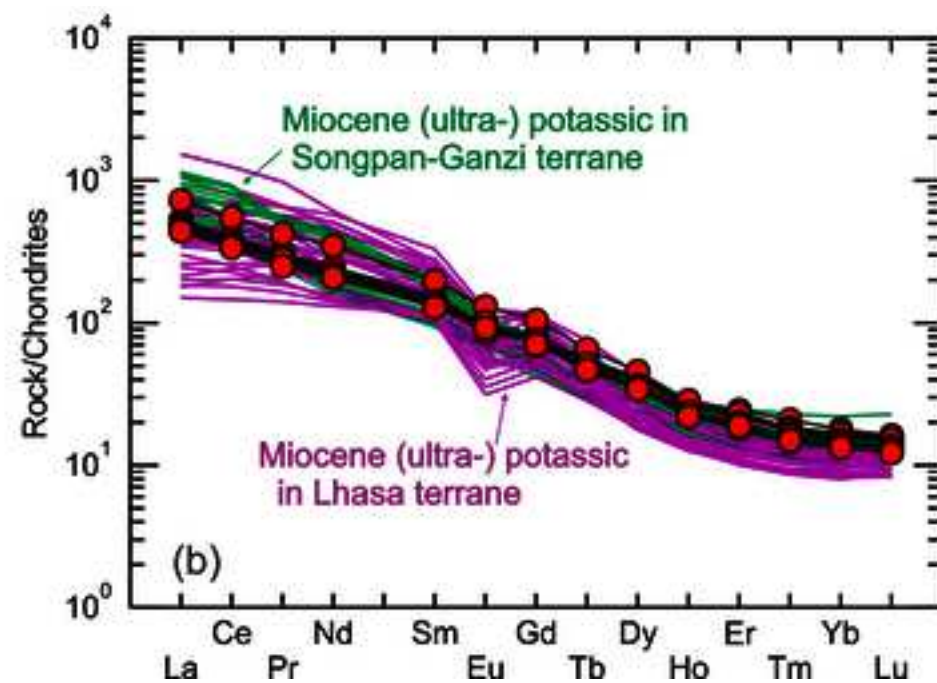
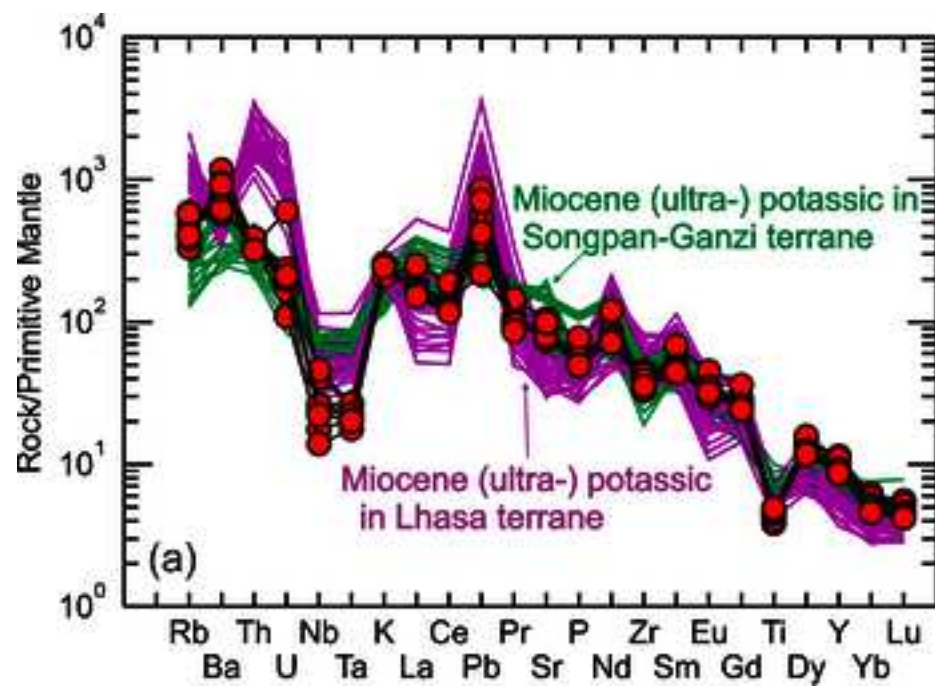


Figure 5

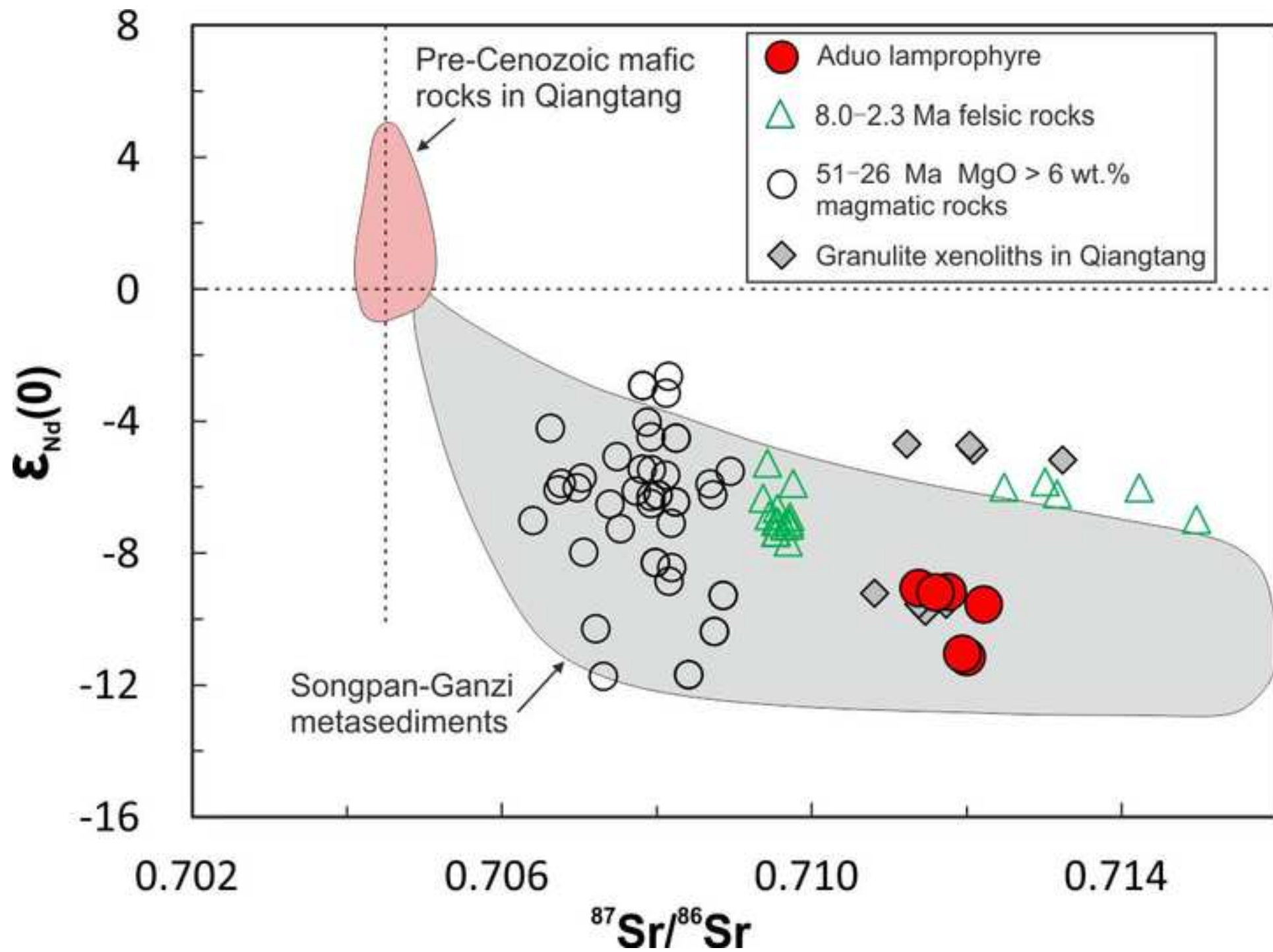


Figure 6

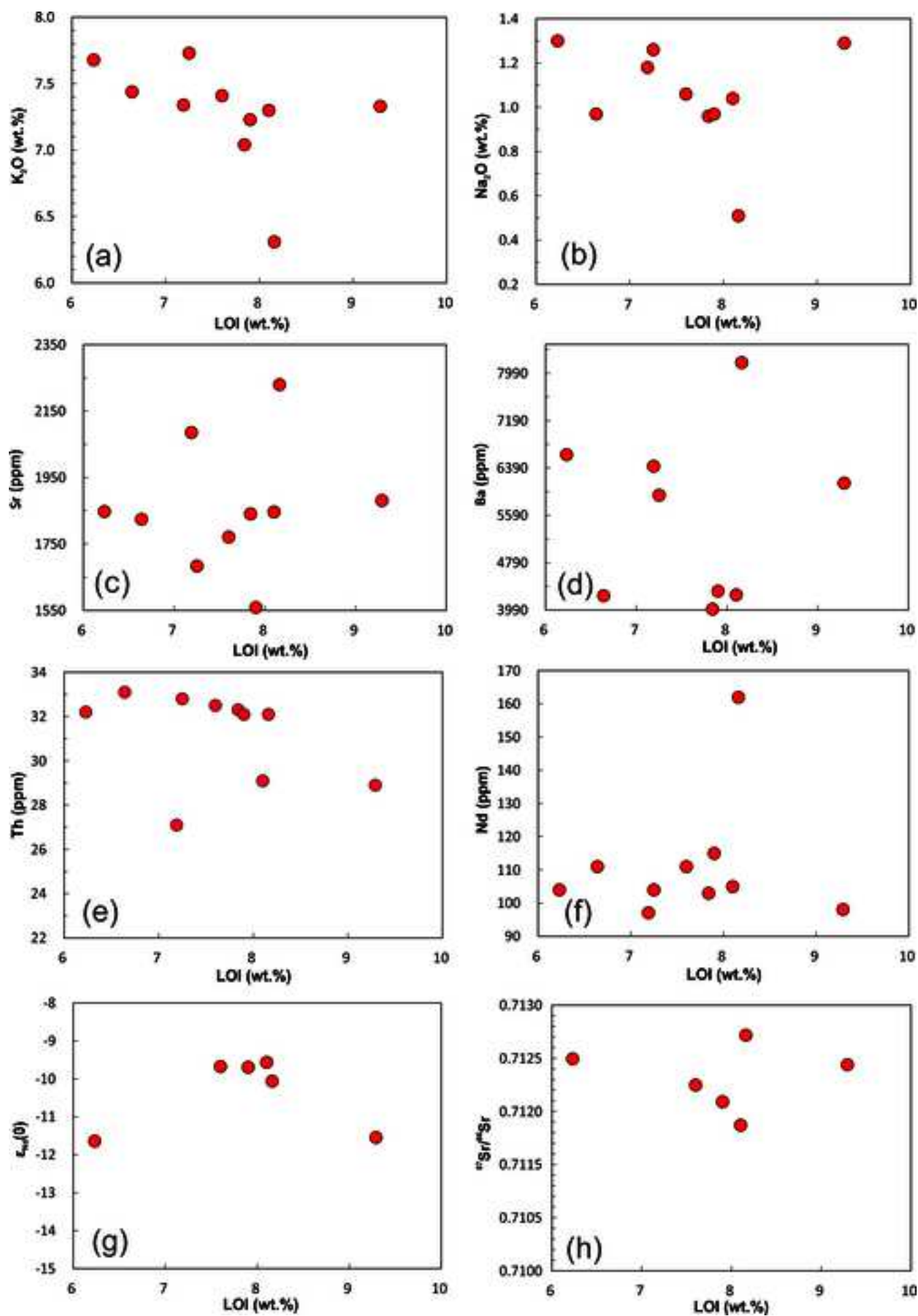
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Figure 7

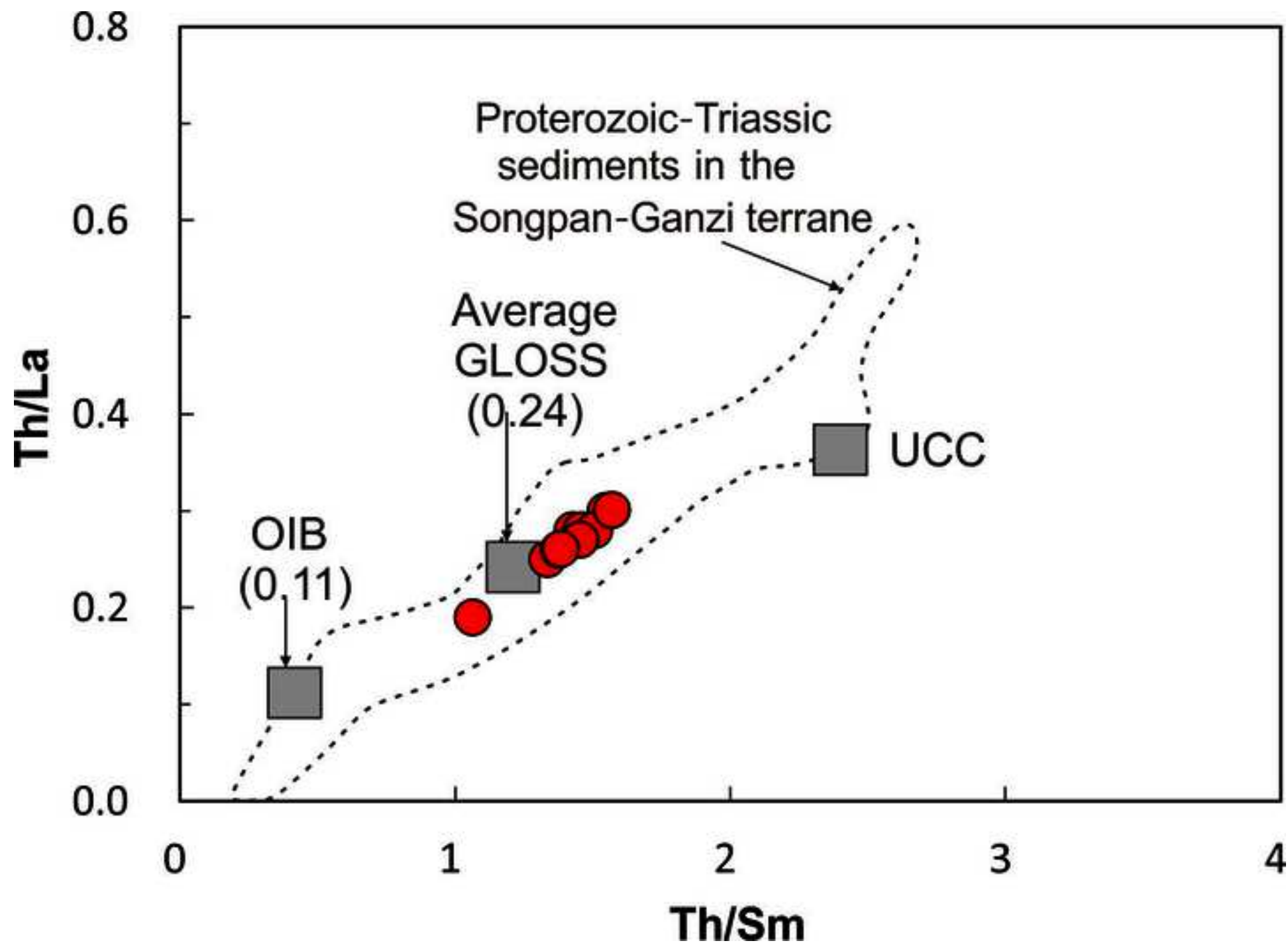


Figure 8

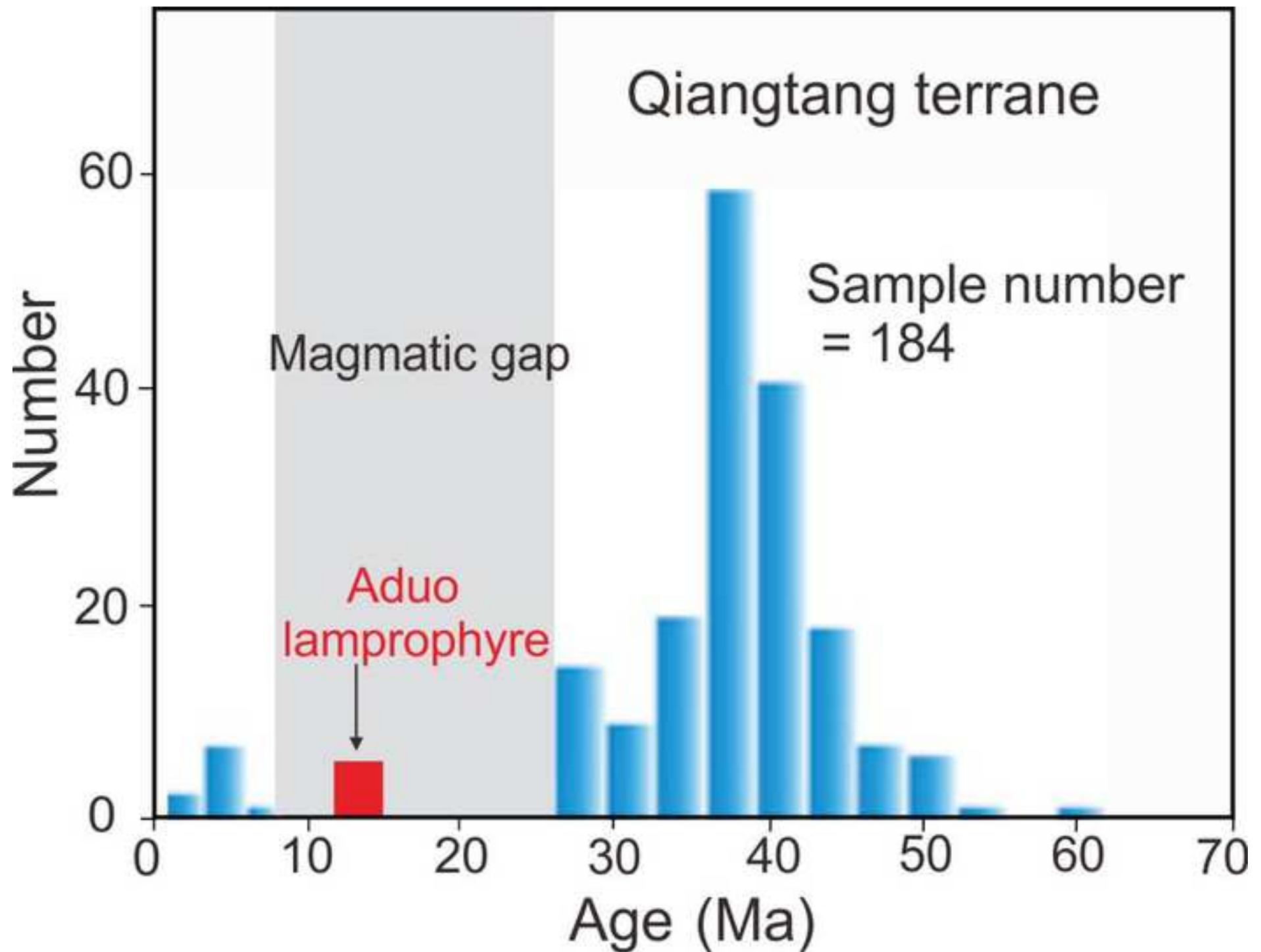
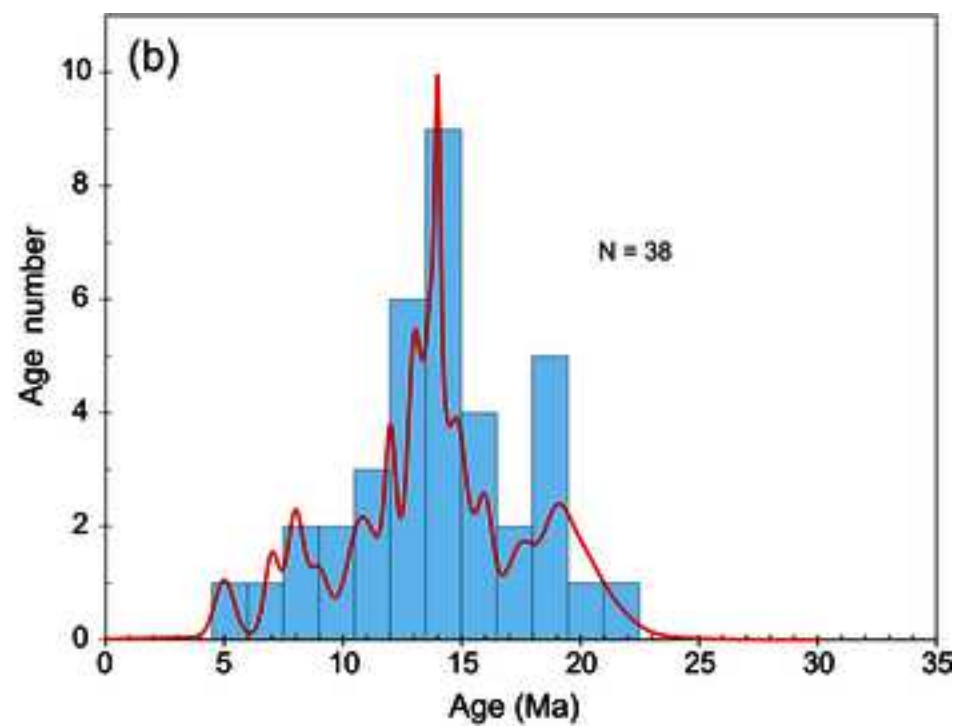
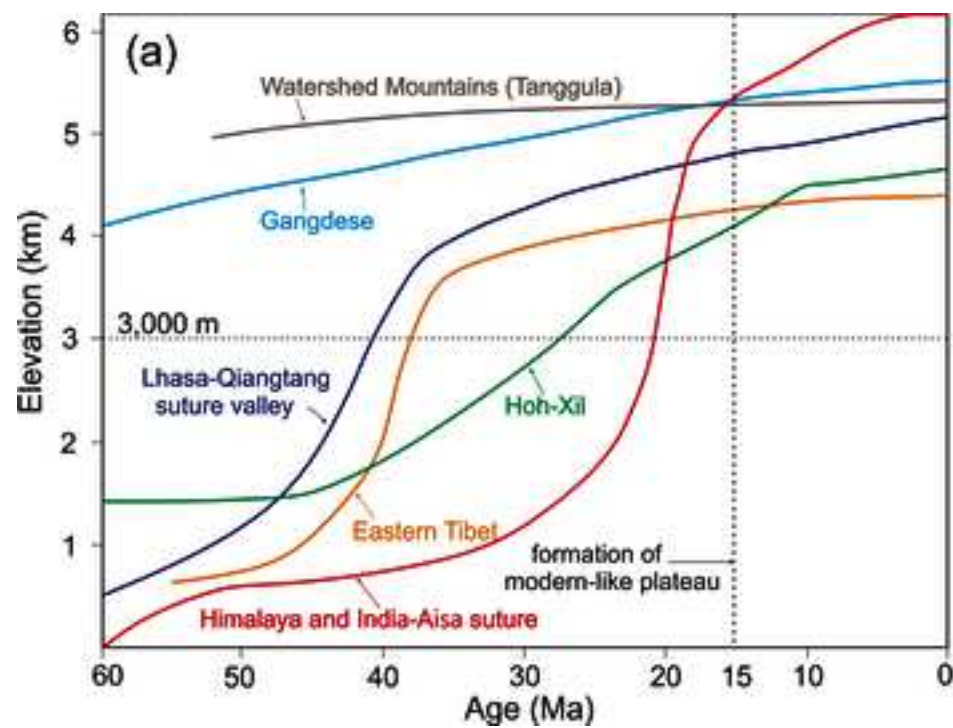


Figure 9

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**Supplementary material/Appendix (Files for online
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