



High geothermal gradients facilitating lithium mineralization: Insights from the Ke'eryin–Taiyanghe plutons, central China

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ABSTRACT

Understanding the critical processes that lead to lithium (Li) enrichment is essential for the exploration and development of Li resources—a key component of “low-carbon” energy. The Ke'eryin-Taiyanghe plutons in central China provide a unique opportunity to investigate Li mineralization. The Ke'eryin pluton, a potential parental magma for spodumene-bearing pegmatites, consists of porphyritic biotite granite (KBG) and two-mica granite (KTMG), which crystallized at ~209 Ma and ~202 Ma, respectively. Sr–Nd–Hf–O isotopic compositions suggest that metasedimentary rocks and basaltic basement rocks were the major sources of the Ke'eryin pluton. A positive correlation between Li content in zircons and their $\delta^{18}\text{O}$ values suggests that assimilation of metasedimentary rocks played a significant role in Li enrichment. The KBG is composed primarily of cumulate phases, whereas the KTMG represents the residual melt that underwent Li-rich melt extraction. Consequently, the Ke'eryin pluton cannot represent the parental magma composition of spodumene-bearing pegmatites. The Taiyanghe pluton consists of diorite (TD) and granodiorite (TG), which crystallized at ~210–212 Ma. The TD originated from partial melting of an enriched lithospheric mantle, as indicated by its enriched isotopic signatures. The TG was derived from partial melting of tholeiitic basaltic rocks and metasedimentary rocks. Pressure–temperature estimates indicate the existence of a high geothermal gradient during the Late Triassic, which facilitated crustal assimilation and prolonged magmatic fractionation. We propose that high geothermal gradients are an essential factor in promoting Li-enrichment in magmas. A global compilation of major Li-pegmatite deposits and high-temperature/pressure metamorphic events reveals a close spatiotemporal correlation.

1. Introduction

Lithium is one of the most important resources for achieving the “low-carbon” transition and is receiving widespread global attention from both industry and governmental organizations (Sovacool et al., 2020). Spodumene-bearing pegmatites represent one of the most important sources of Li (Linnen et al., 2012; London, 2018). Crystallization of spodumene requires exceptionally high concentrations of Li in the melt (≥ 7000 ppm), ~300 times the average Li content of the upper

continental crust (Maneta et al., 2015; Rudnick and Gao, 2003). Significant debates persist regarding how such a high concentration of Li is achieved in magma to form spodumene (Cerný et al., 2012; Koopmans et al., 2023; Li et al., 2023; London, 2018; Lv et al., 2021; Simmons et al., 2016). Three major hypotheses have been proposed to explain Li mineralization: (1) extreme fractionation of crustal-derived magma; (2) direct partial melting of a Li-rich sedimentary source; and (3) multi-stage partial melting.

The first hypothesis proposes that extreme fractionation of crust-

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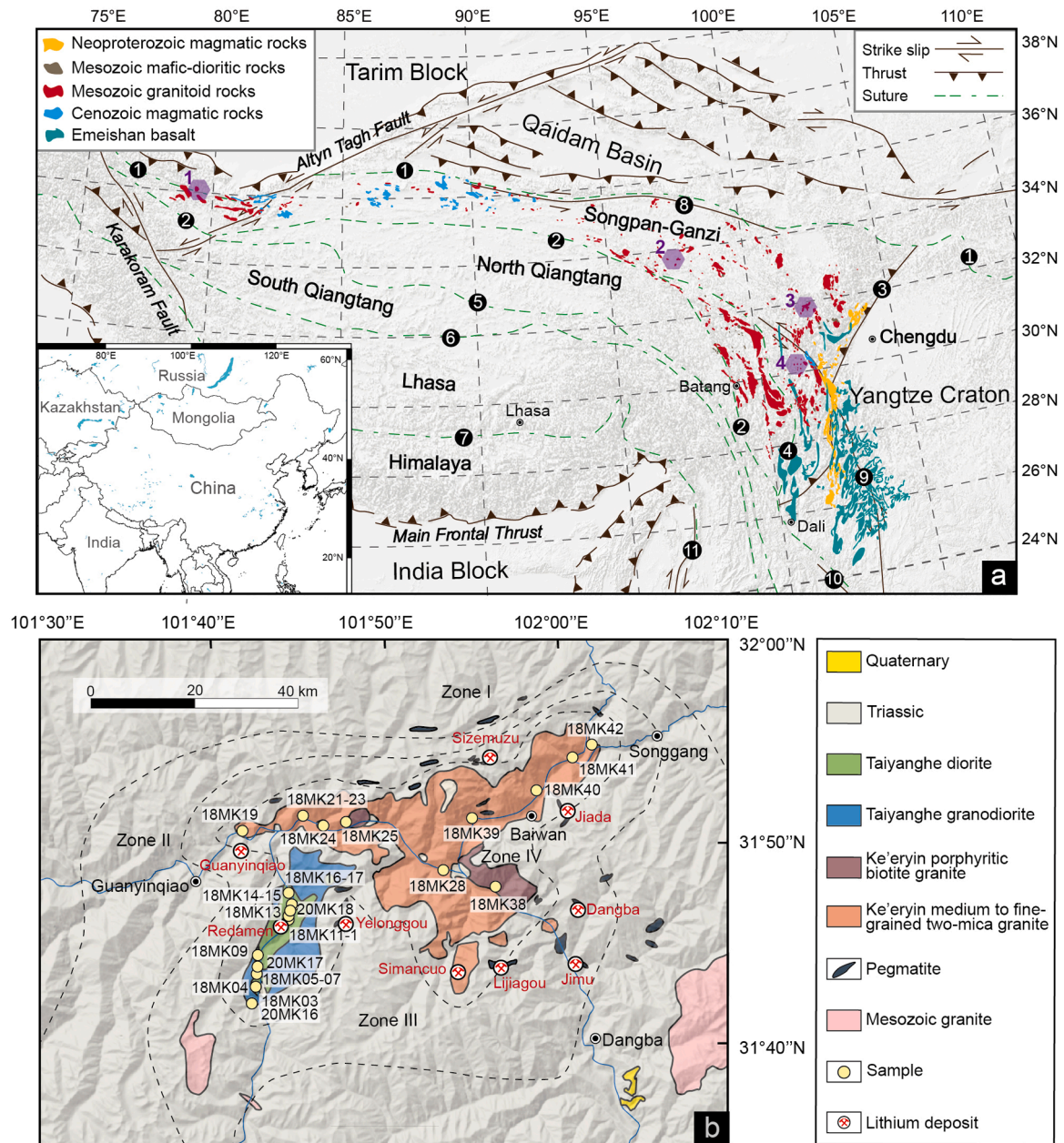


Fig. 1. Maps of the Tibetan Plateau and Ke'eryin-Taiyanghe plutons. (a) Distributions of Emeishan basalt and magmatic rocks in the Songpan-Ganzi terrane and western Yangtze Craton (modified after [Hu et al., 2024, 2022b](#); [Shellnutt, 2014](#); [Xu et al., 2020](#); [Zhao et al., 2018](#) and references therein). Numbers represent suture zones and major faults: 1-Eastern Kunlun-Animaqing suture zone; 2-Jinshajiang suture zone; 3-Longmenshan thrust fault; 4-Ganzi-Litang suture zone; 5-Longmu-co-Shuanghu suture zone; 6-Bangong-Nujiang suture zone; 7-Indus-Yarlung Zangbo suture zone; 8-Kunlun fault; 9-Xianshuihe-Xiaojiang fault; 10-Ailaoshan-Honghe fault; 11-Sagaing fault. The purple hexagons indicate the locations of Li-pegmatite deposits: 1-Bailongshan; 2-Zhawulong-Caolong; 3-Ke'eryin; 4-Jiajika. (b) Simplified geologic map of Ke'eryin-Taiyanghe plutons (modified after [Deschamps et al., 2017](#); [Fei et al., 2020](#)). The metamorphic zonation is after [Zhao et al. \(2019\)](#): Zone I is Mus-Chl zone; Zone II is Bt-And zone; Zone III is Grt-St zone; Zone IV is Sil-Ky zone.

derived magma (e.g., S-type granitic magma) via fractional crystallization and/or melt-melt immiscibility, can enrich the melt sufficiently to form spodumene-bearing pegmatites ([Černý et al., 1985](#); [Dittrich et al., 2019](#); [Liu et al., 2024](#); [London, 2018](#); [Thomas and Davidson, 2016](#); [Wu et al., 2020](#)). This model is supported by field observations of pegmatites that exhibit regional zoning around the parental granite, with more fractionated phases occurring greater distances (e.g., [Trueman and Černý, 1982](#)). The second hypothesis suggests that spodumene-bearing pegmatites can form through direct partial melting of a Li-rich meta-sedimentary source ([Kunz et al., 2022](#); [Lv et al., 2021](#); [Simmons et al., 2016](#); [Zhao et al., 2021](#)). Supporting this model are field observations in which no coeval granites are associated with the pegmatites (e.g.,

[Simmons et al., 2016](#)). Recently, a third hypothesis has been proposed, suggesting that a multi-stage partial melting process may be responsible for the formation of spodumene-bearing pegmatites ([Koopmans et al., 2023](#)). This model proposes that re-melting of a granitic rock, itself formed by partial melting of metasedimentary rocks, could generate a Li-rich melt without extensive fractionation. Such a model has been used to explain the formation of Li-pegmatites in the Chinese Altai ([S. Liu et al., 2024](#)). Although crustal assimilation is often associated with fractional crystallization ([DePaolo, 1981](#)), it is less commonly considered as a major mechanism for Li enrichment due to the relatively low temperatures (e.g., $\leq 800^\circ\text{C}$) of these high silica magmas, where widespread crustal assimilation is energetically unfavorable. However,

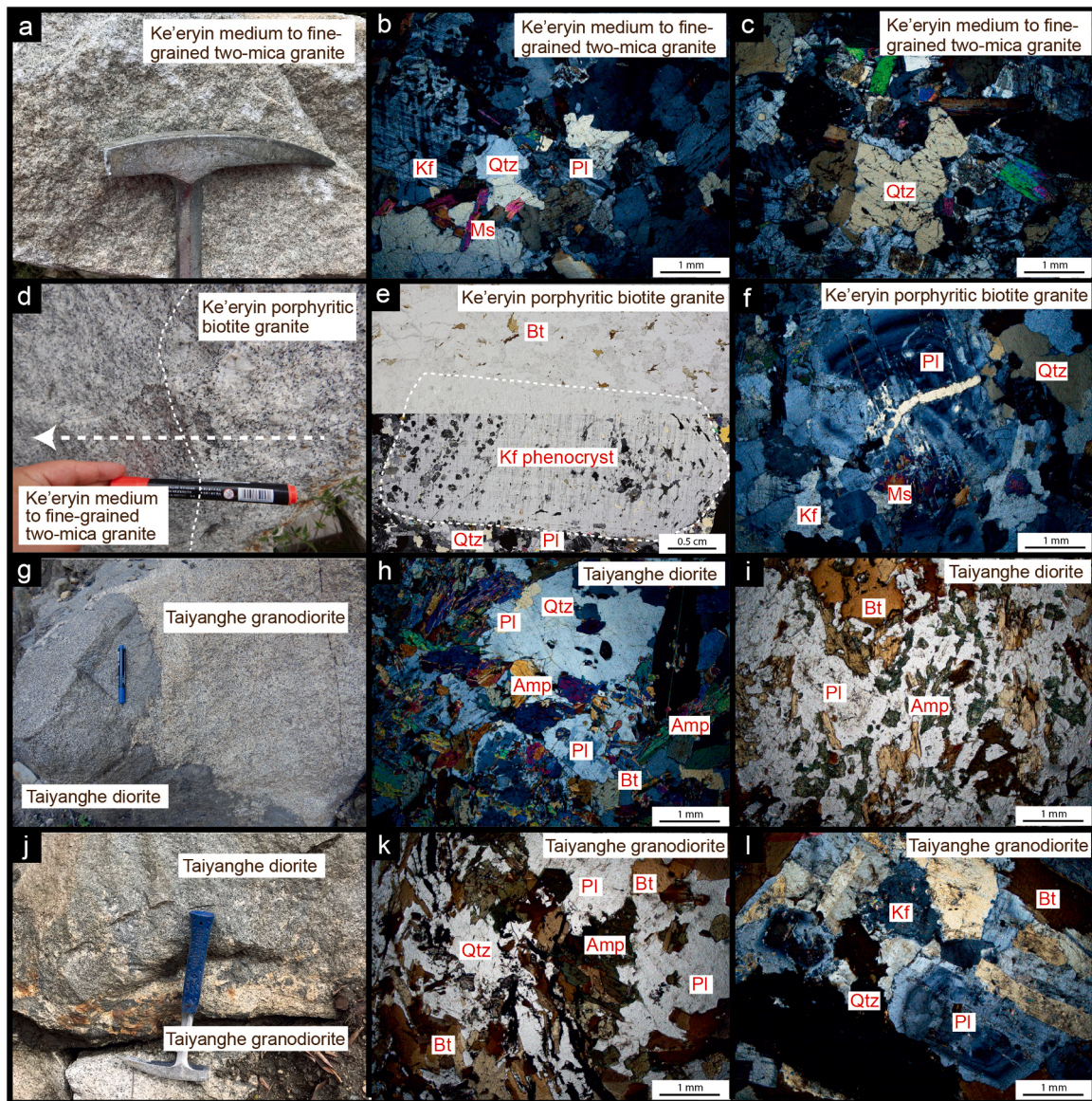


Fig. 2. Outcrop photographs and photomicrographs of the Ke'eryin-Taiyanghe plutons. (a-c) Ke'eryin medium to fine-grained two-mica granite (KTMG) containing K-feldspar, plagioclase, muscovite, and quartz; (d-f) Ke'eryin porphyritic biotite granite (KBG) with K-feldspar as phenocrysts and the plagioclase showing complex compositional zoning; (g-i) Taiyanghe granodiorite (TG) intruding into Taiyanghe diorite (TD), which contains amphibole, biotite, plagioclase with minor quartz; (j-l) Taiyanghe granodiorite, containing biotite, plagioclase, K-feldspar, and quartz with minor amphibole, and the plagioclase showing complex compositional zoning. Mineral abbreviations: Amp, amphibole; Bt, biotite; Pl, plagioclase; Kf, potassic feldspar; Qtz, quartz; Ms, muscovite.

considering that crustal Li is primarily hosted in clastic sedimentary rocks, crustal assimilation may represent a previously overlooked but key process for Li enrichment.

Abundant large Li-mineralized pegmatites developed during the Archean, a period characterized by the relative scarcity of S-type granites and a less evolved continental crust compared with that of the Phanerozoic (McCauley and Bradley, 2014; Roberts et al., 2024). Although source composition and magmatic processes are considered the primary controlling factors for Li mineralization, other factors, such as physical conditions, may also be critical. One remarkable feature of the Archean is its generally higher thermal gradients relative to those of the Phanerozoic (Brown and Johnson, 2019). High geothermal gradients may result in prolonged magmatism and promote crustal assimilation. Consequently, it is reasonable to hypothesize that elevated thermal gradients may facilitate Li mineralization.

To evaluate these hypotheses, this study investigates an intrusive suite associated with a Li-pegmatite deposit in the Songpan-Ganzi

terrane, central China (Fig. 1). The Ke'eryin deposit is one of several super-large Li deposits exposed in the Songpan-Ganzi terrane (Li et al., 2023; Xu et al., 2020). In addition to pegmatites, two chemically distinct plutonic rocks with multiple intrusive phases are exposed around the Ke'eryin deposit, namely, the Ke'eryin pluton (porphyritic biotite granite (KBG) and two-mica granite (KTMG)) and the Taiyanghe pluton (diorite (TD) and granodiorite (TG)). Previous studies have shown that these intrusive phases are coeval with the Li-pegmatites (Deschamps et al., 2017; Fei et al., 2020). The compositional diversity of these plutons provides an excellent opportunity to study the early magmatic evolution of this deposit and can provide new perspectives on the mechanisms of Li mineralization.

In this study, we present an integrated investigation of the petrology, mineralogy, whole-rock geochemistry, and zircon U-Pb-Hf-O isotopic and trace elements characteristics of the Ke'eryin-Taiyanghe plutons, complemented by new thermal modeling to evaluate their emplacement conditions. We constrain the genetic relationships of the different

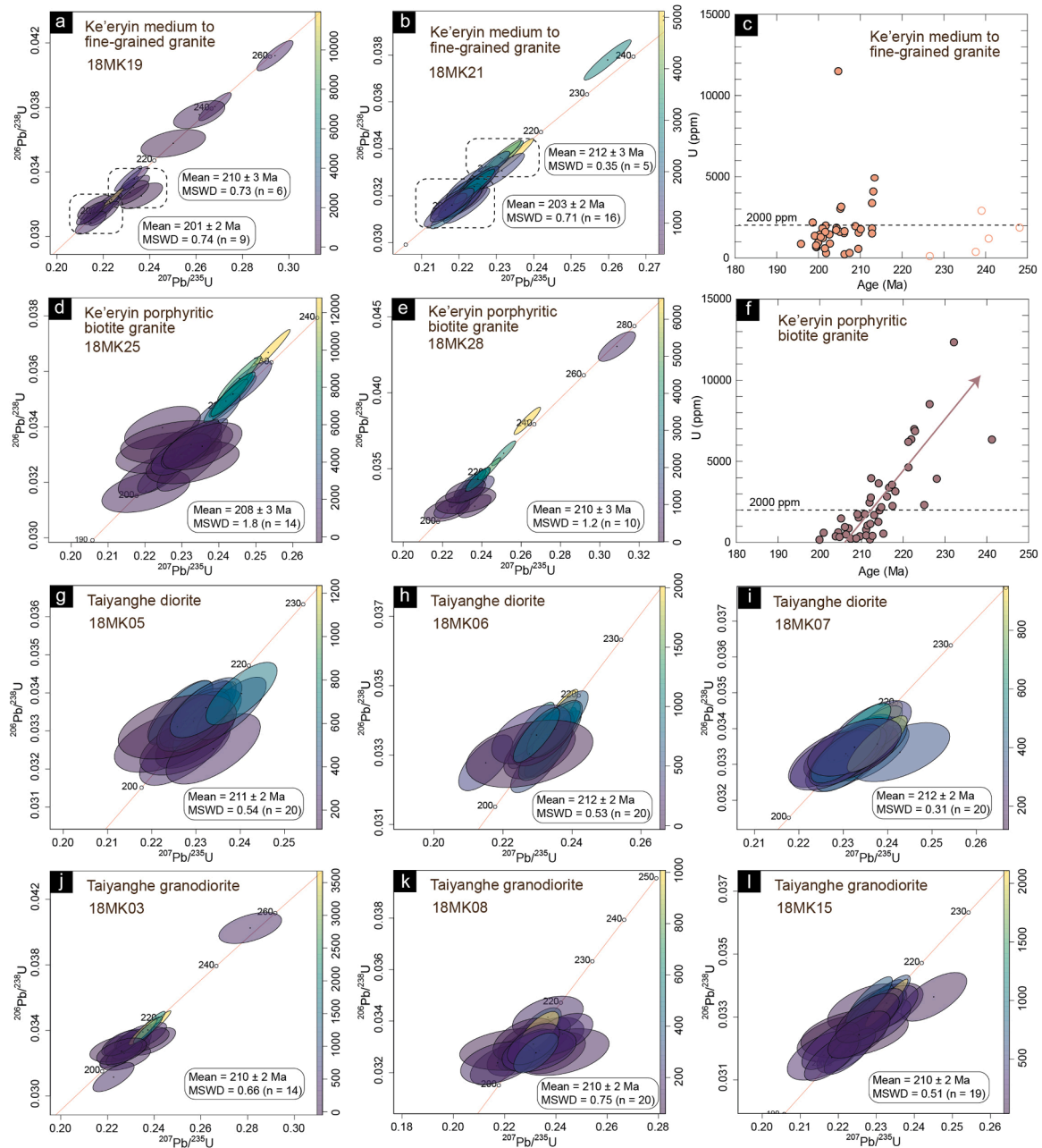


Fig. 3. U–Pb isotopic data for representative samples from the Ke'eryin-Taiyanghe plutons. (a–b) KTMG (18MK19, 18MK21); (c) zircon U content versus apparent U–Pb ages of KTMG, and open circles are inherited zircons; (d–e) KBG (18MK25, 18MK28); (f) zircon U content versus apparent U–Pb ages of KBG showing a positive correlation; (g–i) TD (18MK05, 18MK06, 18MK07); (j–l) TG (18MK03, 18MK08, 18MK15). The colors of data points reflect U content (ppm) of zircons. Data point error ellipses are 2σ .

intrusive phases and explore the critical factors controlling Li mineralization. A key finding of our study is that the magma that produced spodumene-bearing pegmatites experienced extensive crustal assimilation followed by advanced fractional crystallization, with both processes enhanced by high-temperature/pressure (T/P) conditions and elevated geothermal gradients.

2. Geological setting and sampling

2.1. Songpan-Ganzi terrane

The Songpan-Ganzi terrane, extending ~ 2800 km east-west across central China (Fig. 1a; Xu et al., 2020), has been well-studied for its extremely thick (>10 km) turbidite succession, deposited during the

Triassic closure of the Paleo-Tethys Ocean (Enkelmann et al., 2007). The basement of the Songpan-Ganzi terrane is proposed to be Neoproterozoic rocks, similar to those exposed along the western margin of the Yangtze Craton (de Sigoyer et al., 2014; Deschamps et al., 2017; Hu et al., 2022b; Li et al., 2021). In the Songpan-Ganzi terrane, granitic plutons intruded into the turbidites during the late Triassic to early Jurassic under a post-collisional extension setting (Deschamps et al., 2017; Zhang et al., 2007). These plutons exhibit diverse geochemical characteristics, including calc-alkaline I-type, peraluminous S-Type, and peralkaline A-type signatures, and are proposed to have originated from multiple sources with varying contributions from sedimentary rocks via either partial melting or crustal assimilation (de Sigoyer et al., 2014; Deschamps et al., 2017; Hu et al., 2022b; Li et al., 2021; Yuan et al., 2010; Zhang et al., 2007). Late Triassic S-type granites are the

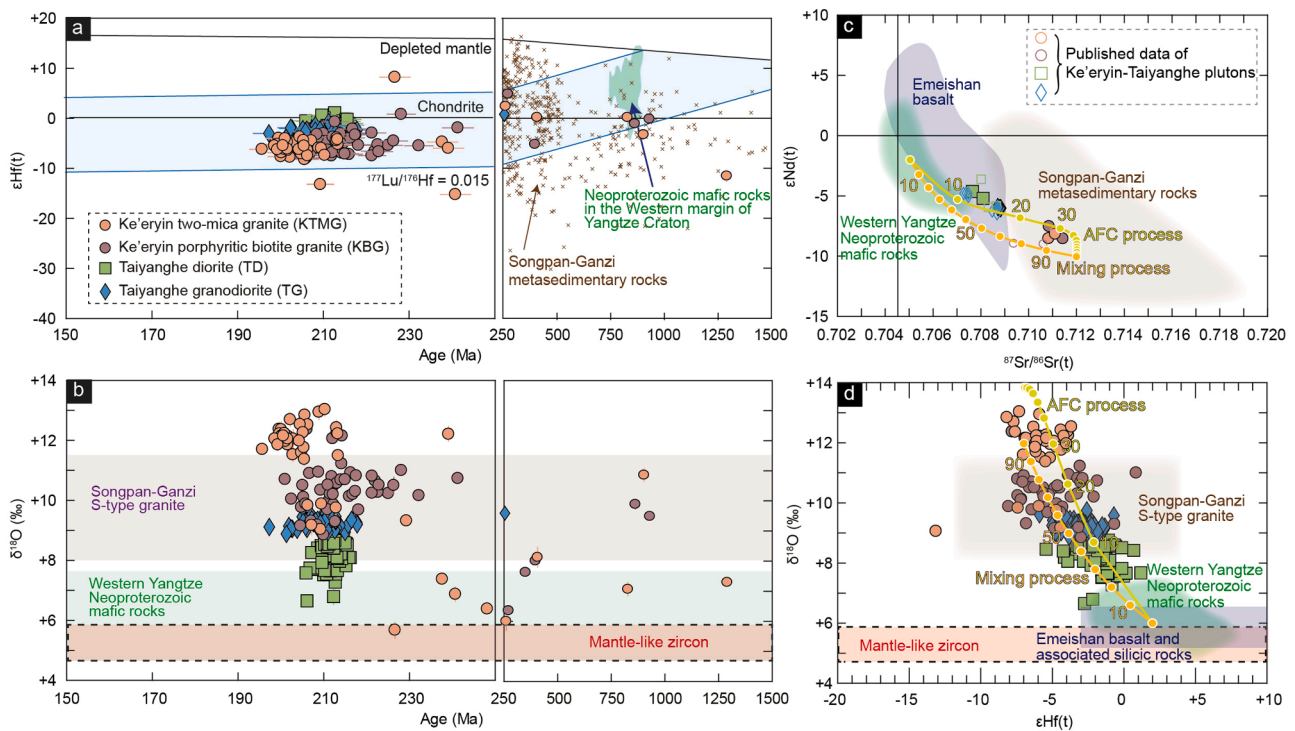


Fig. 4. Zircon Sr-Nd-Hf-O isotopic characteristics for rocks in the Ke'eryin-Taiyanghe plutons. (a) Zircon Hf isotope compositions. (b) Zircon O isotope compositions. (c) Whole-rock Sr-Nd isotope compositions. (d) Zircon Hf-O isotope compositions. Data sources and references used in this figure are listed in the Supplementary Figures. The calculated curves of magma mixing and assimilation-fractional crystallization (AFC) are shown for comparison. Modeling parameters for mixing of Sr-Nd and Hf-O isotopic compositions are listed in Table S4.

predominant igneous rocks associated with Li-pegmatite deposits (e.g., Jiajika) (Fei et al., 2020; Li et al., 2023). Recent estimates indicate that the Songpan-Ganzi terrane may contain over 6 Mt of Li_2O (Yan et al., 2024), marking it one of the most significant Li mineralization belts worldwide.

2.2. Ke'eryin-Taiyanghe plutons and surrounding spodumene-bearing pegmatites

The Ke'eryin-Taiyanghe plutons are located in the eastern part of the Songpan-Ganzi terrane. Their emplacement induced contact metamorphism of Triassic metasedimentary rocks, producing high-temperature, middle-lower pressure metamorphic assemblages, with metamorphic grade systematically decreasing outward from the pluton contacts (Fig. 1b; Zhao et al., 2019).

The Ke'eryin pluton is composed of KTMG and KBG (Fig. 2a-f). The KTMG is medium- to fine-grained, consisting of quartz, K-feldspar, plagioclase, biotite, and muscovite, with accessory minerals including zircon, monazite, and apatite (Fig. 2b and c). The KBG displays a transitional contact relationship with the KTMG, consisting of phenocrystic K-feldspar in a quartz, K-feldspar, plagioclase, and biotite matrix (Fig. 2e and f). Plagioclase in the KBG exhibits reverse zoning, reflecting a complex magmatic evolutionary history (Fig. 2f). Minor muscovite granites, occurring as stocks at the rim of the Ke'eryin pluton, intruded into the Triassic strata (Yan et al., 2024). According to previous studies, the Ke'eryin pluton is a typical S-type granite that underwent an extended period of emplacement and chemical evolution (231–209 Ma) (Table S1; de Sigoyer et al., 2014; Deschamps et al., 2017).

The Taiyanghe pluton is adjacent to the Ke'eryin pluton and is composed of TD and TG (Fig. 2g-l). The TD is at the center of the Taiyanghe pluton and comprises quartz, plagioclase, amphibolite, and biotite, with accessory mineral including titanite, apatite, and zircon (Fig. 2h and i). The TG displays an intrusive contact relationship with the TD (Fig. 2g and j) and is composed of quartz, K-feldspar, plagioclase,

amphibole, and biotite, with accessory minerals including allanite, apatite, monazite, and zircon (Fig. 2k and l). Plagioclase in the TG also displays a reverse zoning texture (Fig. 2l). Deschamps et al. (2017) argued that the Taiyanghe pluton originated from partial melting of enriched mantle with an extended emplacement history involving prolonged magmatic fractionation and crystal accumulation (Table S1). Conversely, a recent study suggested that the Taiyanghe pluton was derived from partial melting of crustal materials (Li et al., 2021).

Abundant pegmatites surround the Ke'eryin pluton, displaying a regional zonation with barren pegmatites located closer to the pluton (Yan et al., 2024). Among these, spodumene-bearing pegmatite dikes primarily intrude into Triassic turbidites (Fig. 2), except for the Redamen pegmatite, which intrudes into the Taiyanghe pluton (Fei et al., 2021; Li et al., 2023; Yan et al., 2024). These dikes range from 0.5 to 70 m in width with no distinct internal zonation (Yan et al., 2024). Several Li deposits, such as Jiada, Lijiagou, and Yelonggou, are estimated to contain over 3 Mt of Li_2O (Fei et al., 2020; Li et al., 2023; Yan et al., 2024). U-Pb dating of cassiterite and columbite-group mineral indicates that spodumene-bearing pegmatites were primarily formed at ~211–204 Ma (Table S1; Fei et al., 2020; Hu et al., 2024; Li et al., 2022), exhibiting a strong spatial and temporal connection to the Ke'eryin pluton. However, competing models have been proposed for the formation of these Li-pegmatites. Some researchers have suggested that these Li-pegmatites were derived from low-degree partial melting of metasedimentary rocks and are not genetically related to the Ke'eryin granite (Fei et al., 2021, 2020). In contrast, other studies propose that the Li-pegmatites formed through extreme magmatic fractionation of granitic magma and coupled with fluid exsolution (Li et al., 2023, 2022; Yan et al., 2024).

In this study, we collected 32 samples from the Ke'eryin-Taiyanghe plutons (Fig. 2), including 9 samples of KTMG, 3 samples of KBG, 10 samples of TD, and 10 samples of TG, covering the majority of both plutons. All samples were fresh, with alteration or metasomatic minerals, such as chlorite, epidote, sericite, and albite, rarely observed.

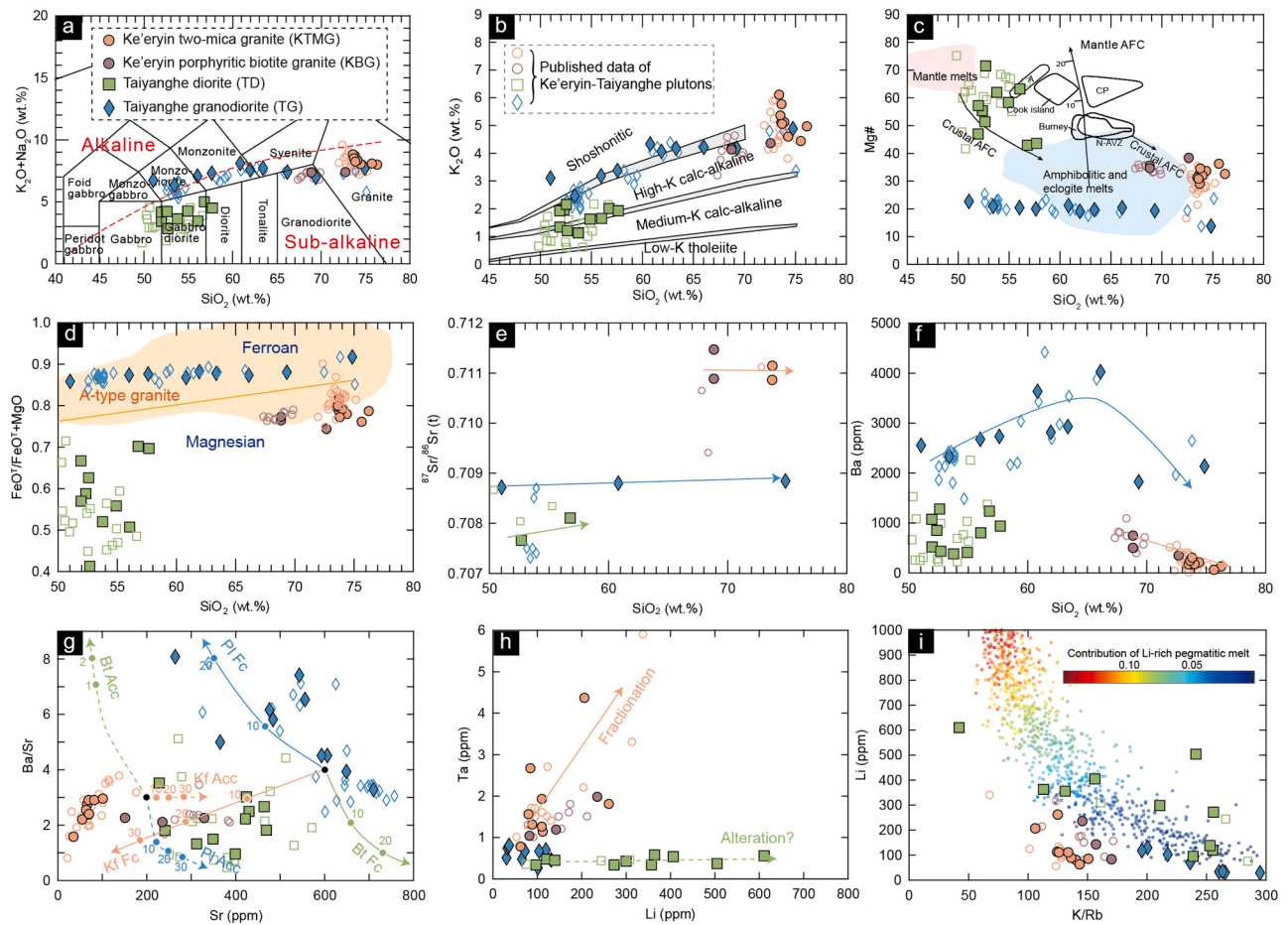


Fig. 5. Major and trace element compositions of samples from the Ke'eryin-Taiyanghe plutons. (a) Total alkalis vs silica diagram. (b) K_2O vs. SiO_2 classification diagram. (c) $Mg\#$ vs. SiO_2 diagram. (d) FeO^T/FeO^T+MgO vs. SiO_2 diagram. (e) $^{87}Sr/^{86}Sr(t)$ vs. SiO_2 (wt.%) diagram. (f) Ba (ppm) vs. SiO_2 (wt.%) diagram. (g) Ba/Sr vs. Sr (ppm) diagram. The solid curves represent trends of fractional crystallization (Fc) and dashed curves represent trends crystal accumulation (Acc). The parameters used in the modeling are listed in Table S7. (h) Ta (ppm) vs. Li (ppm) diagram. (i) Li (ppm) vs. K/Rb diagram. A Monte Carlo simulation is performed to show the effect of addition of a Li-rich melt (Li: 7200 ppm; K: 24707 ppm; Rb: 1000 ppm) to a low-Li dioritic melt (Li: 75 ppm; K: 10790 ppm; Rb: 38 ppm). The compositions of two endmembers are based on the average composition of spodumene-bearing pegmatites (Fei et al., 2020; Yan et al., 2024) and the most primitive TD sample (Li et al., 2021). The open symbols are the previously published data of Ke'eryin-Taiyanghe plutons (Deschamps et al., 2017; Li et al., 2021; Yuan et al., 2010; Yue et al., 2019, 2018). The sources of original diagrams of (a-d) are shown in the Supplementary Figures.

3. Results

We performed whole-rock geochemical and Sr-Nd isotopic analyses at the Wuhan SampleSolution Analytical Technology Co., Ltd., China. *In-situ* zircon U-Pb-Hf-O isotopic analyses and mineral geochemical analyses were conducted at the Institute of Geology and Geophysics, Chinese Academy of Sciences, China. Detailed analytical methods are listed in Supplementary Methods. The analytical results are as below.

3.1. Zircon U-Pb ages, and Hf-O isotopes

The analytical results of the U-Pb isotopic and trace element data are listed in Table S2, while the Lu-Hf and O isotopic data are provided in Table S3.

All zircon grains are euhedral and exhibit typical magmatic textures, characterized by oscillatory, sector, and banded zoning in cathodoluminescence images (Fig. S1; Corfu et al., 2003). Some zircons from the Ke'eryin granites exhibit core-rim textures consistent with inherited (xenocrystic) zircon cores. Nearly no inherited zircon cores were observed in zircons from the TD and TG (Fig. S1). All these zircons are mainly short to long prismatic in shape, with lengths of 100–400 μm and length/width ratios of 1:1–5:1; those from TD and TG are slightly larger than those from KBG and KTMG (Fig. S1).

Fourteen analyses of KTMG samples (18MK19 and 18MK21) yielded older apparent $^{206}Pb/^{238}U$ ages ranging from 227 Ma to 1900 Ma (Fig. 3a-b). Based on their Hf-O isotopic compositions ($\epsilon Hf(t) = -16.2$ – -8.3 ; $\delta^{18}O = 5.7\%$ – 12.2%) (Fig. 4), these zircons were interpreted to as captured or inherited. The remaining data were concordant, clustering into two age populations with weighted mean $^{206}Pb/^{238}U$ ages of 210 ± 3 (MSWD = 0.73) to 212 ± 3 Ma (MSWD = 0.35) and 201 ± 2 (MSWD = 0.74) to 203 ± 2 Ma (MSWD = 0.71) (Fig. 3a-b). The younger zircons yielded $\epsilon Hf(t)$ values of -7.7 to -3.7 and $\delta^{18}O$ values of 9.8% to 12.7% . The older zircons exhibited $\epsilon Hf(t)$ values of -13.2 – -3.9 and $\delta^{18}O$ values of 9.0% – 13.0% (Fig. 4a-b). We interpreted the younger age population to reflect the crystallization age of the pluton. The older age population may correspond to antecrystic zircons, which are early crystallized zircons, as indicated by their core-rim textures (Fig. S1, Siégl et al., 2018), or may represent anomalously old ages due to high U concentrations (up to ~ 5000 ppm), a known cause of older dates in secondary ion mass spectrometry (SIMS) analyses (c.f., Li et al., 2010).

For the KBG samples (18MK25 and 18MK28), five analyses yielded relatively old apparent $^{206}Pb/^{238}U$ ages (930–272 Ma) with $\epsilon Hf(t)$ values of -5.2 – $+4.7$ and $\delta^{18}O$ values of 6.4% – 9.9% . The remaining data showed a wide range of ages and exhibited a positive correlation between U content and $^{206}Pb/^{238}U$ age (Fig. 3d-f), which is interpreted as reflecting high-U effect in SIMS analyses (Li et al., 2010). Only zircon

grains with U < 2000 ppm were considered for crystallization age interpretations. Therefore, the KBG samples have weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 208 ± 3 (MSWD = 1.8) and 210 ± 3 Ma (MSWD = 1.2) (Fig. 3d-e). These zircons yielded $\epsilon\text{Hf}(t)$ values of -8.1 to -0.7 and $\delta^{18}\text{O}$ values of 8.9‰ to 12.4‰ (Fig. 4a-b).

All analyses of TD samples (18MK05, 18MK06, and 18MK07) were concordant and yielded weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 211 ± 2 (MSWD = 0.54), 212 ± 2 (MSWD = 0.53), and 212 ± 3 Ma (MSWD = 0.31) (Fig. 3g-i), which are interpreted as crystallization ages. The analyses had initial $\epsilon\text{Hf}(t)$ values of -5.4 to $+1.2$, and $\delta^{18}\text{O}$ values of 6.7‰ to 8.8‰ (Fig. 4a-b).

Except for one analysis of sample 18MK03, all TG samples (18MK03, 18MK08, and 18MK15) yielded consistent weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 210 ± 2 (MSWD = 0.66), 210 ± 2 (MSWD = 0.75), and 210 ± 2 Ma (MSWD = 0.51) (Fig. 3j-l), which are considered crystallization ages. These zircons yielded initial $\epsilon\text{Hf}(t)$ values of -5.9 to -0.7 , and $\delta^{18}\text{O}$ values of 8.9‰ to 9.8‰ (Fig. 4a-b).

3.2. Whole-rock geochemical compositions and Sr-Nd isotopes

The major and trace element compositions of the samples from the Ke'eryin-Taiyanghe plutons are listed in Table S5. Overall, all samples showed low loss-on-ignition values (primarily <1 wt.%), indicating limited post-magmatic alteration or fluid metasomatism, and the obtained whole-rock data can be considered representative.

The KTMG exhibits high SiO_2 content (73.6–76.3 wt.%) and belongs to the high-K calc-alkaline, strongly peraluminous rock series ($A/\text{CNK} = 1.10\text{--}1.20$) (Fig. 5a and b). These samples display low Mg# (29–36), low Ba (56–300 ppm), and high Rb/Sr ratios (3.27–8.13) (Fig. 5), with Li contents (63–262 ppm) showing considerable variation (Fig. 5h). These samples display fractionated chondrite-normalized rare earth element (REE) patterns with strongly negative Eu anomalies ($\delta\text{Eu} = 0.20\text{--}0.46$) (Fig. S2) ($\delta\text{Eu} = \text{Eu}_N/\text{SQRT}(\text{Sm}_N \cdot \text{Gd}_N)$; subscript N represents the chondrite-normalized value; Sun and McDonough, 1989). They have high concentrations of large ion lithophile elements (LILEs), such as Rb and K, and exhibit moderate to strong negative Nb-Ta-Ti and Ba-Sr anomalies in primitive mantle-normalized multi-element patterns (Fig. S2). The KTMG samples show enriched Sr-Nd isotopic compositions with initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7109–0.7111 and $\epsilon\text{Nd}(t)$ values of -8.2 to -8.5 (Fig. 4c).

Compared to the KTMG samples, the KBG samples have slightly lower SiO_2 contents (68.9–72.7 wt.%), higher Mg# (35–38) and Ba (342–740 ppm), and lower Rb/Sr ratios (0.61–1.62) and A/CNK values (1.06–1.20) (Fig. 5). They display trace element patterns similar to those of the KTMG samples but have weak to strongly negative Eu anomalies ($\delta\text{Eu} = 0.54\text{--}0.78$) and no negative Sr anomalies (Fig. S2). The KBG samples also exhibit nearly identical Sr-Nd isotopic compositions compared to those of the KTMG samples ($^{87}\text{Sr}/^{86}\text{Sr}(t) = 0.7109\text{--}0.7115$; $\epsilon\text{Nd}(t) = -8.5\text{--}7.5$) (Fig. 4c).

The TD samples have low SiO_2 contents (51.9–57.7 wt.%) and high Mg# values (43–72), belonging to the medium to high-K calc-alkaline rock series (Fig. 5). Notably, the TD samples exhibit high Li contents (97–611 ppm) (Fig. 5h and i), even higher than those of the Ke'eryin granites. They are also enriched in LREE and LILEs, with no or weakly negative Eu anomalies ($\delta\text{Eu} = 0.62\text{--}1.13$) (Fig. S2). Their Sr-Nd isotopic compositions ($^{87}\text{Sr}/^{86}\text{Sr}(t) = 0.7077\text{--}0.7081$; $\epsilon\text{Nd}(t) = -5.2\text{--}4.6$) are considerably less enriched than those of the Ke'eryin granites (Fig. 4c).

The TG samples have wide ranges of SiO_2 contents (51.0–74.9 wt.%) and low Mg# values (14–23), with weakly peraluminous ($A/\text{CNK} = 1.02\text{--}1.09$) characteristics (Fig. 5). These rocks belong to the shoshonitic to high-K calc-alkaline and ferroan rock series (Fig. 5b and d). Notably, they exhibit high Ba (1824–4026 ppm) and Zr (175–632 ppm) contents (Fig. 5f). In addition, they show strongly fractionated REE patterns with no distinct Eu anomalies ($\delta\text{Eu} = 0.71\text{--}1.40$) (Fig. S2). They exhibit Sr-Nd isotopic compositions similar to those of the TD samples with $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7087–0.7088 and $\epsilon\text{Nd}(t)$ values of -6.0 to -5.9

(Fig. 4c).

3.3. Mineral compositions and thermobarometry

Representative major element compositions of amphibole, biotite, and feldspar from the Ke'eryin-Taiyanghe plutons are listed in Table S6.

Amphiboles from the TD are mainly magnesiohornblende (Hawthorne et al., 2012), exhibiting a relatively wide range of Mg# values (42–76) (Fig. S3). The calculated temperatures range from 742 to 862°C (average $809^\circ\text{C} \pm 29$ (std)), and the calculated pressures range from 2.0 to 6.5 kbar (average $3.3 \text{ kbar} \pm 1.0$ (std)), based on the machine learning-based thermobarometry method of Higgins et al. (2021). The amphiboles in the TG are rare and classified as ferrotschermakite (Fig. S3). They display low Mg# values (20–23) and the calculated P-T conditions are $857^\circ\text{C} \pm 9$ (std) and $8.9 \text{ kbar} \pm 0.8$ (std), respectively. The uncertainties of calculated T-P are approximately 40°C and 1.5 kbar. Because of the slight differences in amphibole Na_2O content between our samples and the experiments used to calibrate the thermobarometer (Fig. S4), the estimated P-T conditions may deviate from the actual values.

Biotites from the KTMG are predominately Fe^{2+} -biotite with low Mg# values (22–28) (Fig. S3). Their chemical compositions indicate crystallization from a peraluminous magma (Fig. S3). According to a machine learning thermobarometry (Li and Zhang, 2022), the calculated temperatures and pressures are $754^\circ\text{C} \pm 8$ (std) and $6.1 \text{ kbar} \pm 0.7$ (std), respectively. Biotites from the KBG exhibit chemical compositions similar to those of the KTMG with higher Mg# values (34–38). The calculated T-P conditions are also slightly higher than those of the KTMG ($T = 811 \pm 10^\circ\text{C}$; $P = 9.5 \pm 1.0 \text{ kbar}$). Biotites from the TD are Mg-biotite with high Mg# values (43–66). Their chemical compositions suggest crystallization from a calc-alkaline magma (Fig. S3). The calculated T-P conditions are $817^\circ\text{C} \pm 23$ (std) and $8.6 \text{ kbar} \pm 0.8$ (std), respectively. Biotites from the TG are mainly Fe^{2+} -biotite with very low Mg# values (11–26). Owing to their high FeO and Al_2O_3 contents, they are interpreted to have crystallized from a peraluminous, alkaline magma (Fig. S3). The inferred T-P conditions of the magma are $768^\circ\text{C} \pm 12$ (std) and $7.5 \text{ kbar} \pm 1.1$ (std), respectively. The uncertainties of the calculated T-P conditions are approximately 54°C and 1.27 kbar, respectively. Overall, the chemical compositions of the analyzed biotites closely match those used for the calibration of the thermometer (Fig. S4), indicating that the obtained T-P conditions are reliable.

Plagioclase minerals from the Ke'eryin-Taiyanghe plutons exhibit a wide compositional range (Fig. S3). In the KTMG, plagioclase is mainly oligoclase to albite ($\text{An} = 4\text{--}15$), whereas in the KBG, it primarily ranges from andesine to oligoclase ($\text{An} = 23\text{--}54$). In the TD, plagioclase is bytownite to andesine ($\text{An} = 36\text{--}82$), and in the TG, it ranges from labradorite to oligoclase ($\text{An} = 18\text{--}58$). Notably, plagioclase in the KTMG, TD, and TG exhibits complex zoning, including normal and reverse zoning within individual crystals, reflecting compositional variations during crystallization (Fig. S3).

4. Discussion

4.1. Formation age and duration of the Ke'eryin-Taiyanghe plutons

Previous geochronological studies of the Ke'eryin-Taiyanghe plutons yielded contrasting results. Roger et al. (2004) obtained a U-Pb thermal ionization mass spectrometry age of 153 Ma using dissolved zircon fractions for the Ke'eryin pluton. However, a recent study by Deschamps et al. (2017) reported that the Ke'eryin pluton shows a wide range of individual zircon U-Pb laser ablation inductively coupled plasma mass spectrometry dates (230–200 Ma), which they interpreted as evidence for a prolonged emplacement and crystallization history (~30 Myr). Our new zircon U-Pb SIMS analyses of the Ke'eryin pluton yielded slightly different ages (Fig. 3). The crystallization age of the KTMG was determined to be ~202 Ma, and that of the KBG was ~209 Ma. Early Triassic

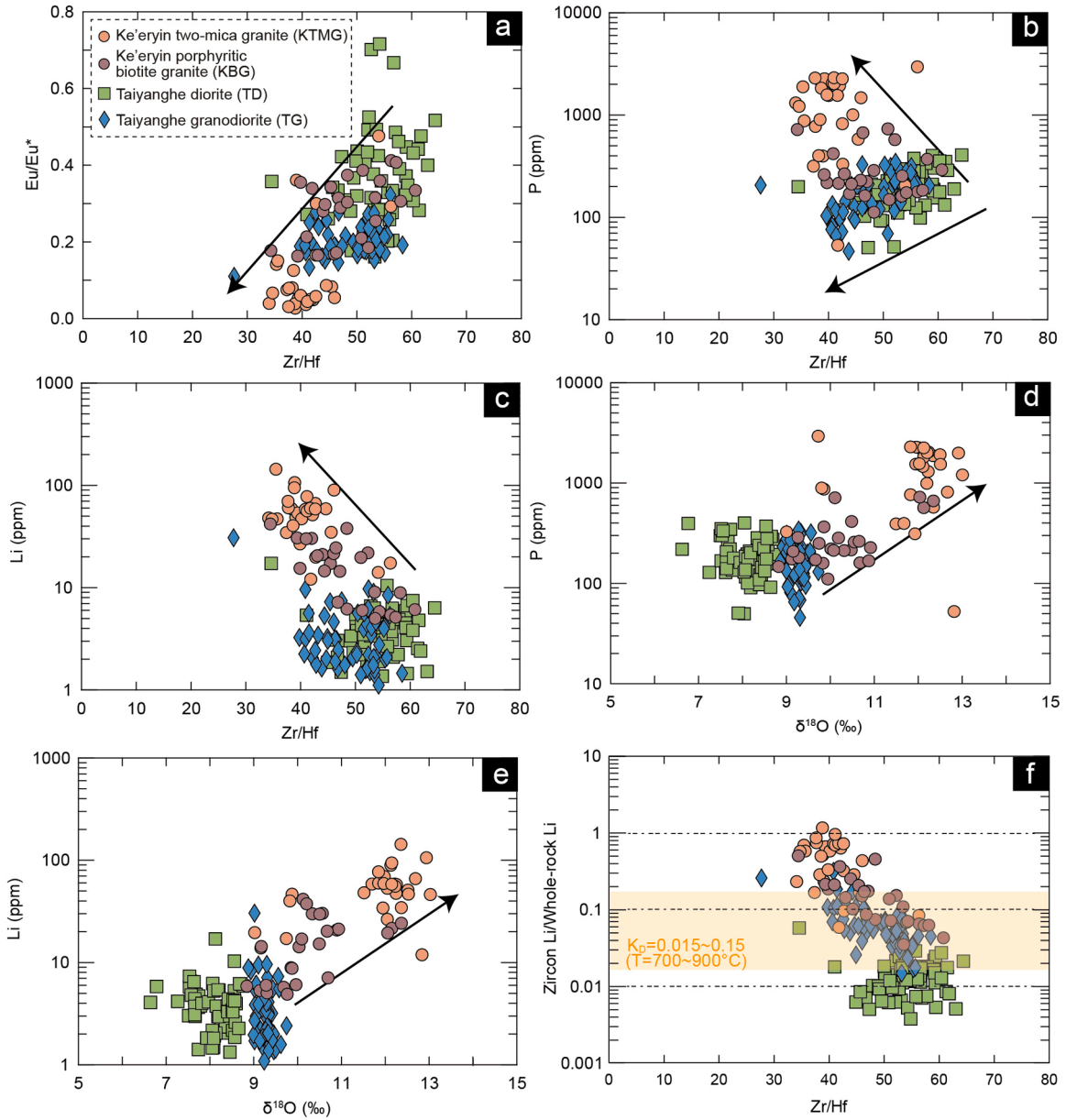


Fig. 6. Chemical and isotopic compositions of zircons from Ke'eryin-Taiyanghe plutons. (a) Eu/Eu^* vs. Zr/Hf diagram. (b) P (ppm) vs. Zr/Hf diagram. (c) Li (ppm) vs. Zr/Hf diagram. (d) P (ppm) vs. $\delta^{18}\text{O}$ (‰) diagram. (e) Li (ppm) vs. $\delta^{18}\text{O}$ (‰) diagram. (f) Zircon $\text{Li}/\text{Whole-rock Li}$ vs. Zr/Hf diagram. The range of K_p is based on the experimental results (Wang and Trail, 2022).

(~250–215 Ma) and older zircon U-Pb dates are interpreted as inherited zircons. This interpretation is supported by their distinct $\delta^{18}\text{O}$ values relative to those with ages < 215 Ma (Fig. 4b), as well as by the consistency of these older ages with those reported for the Songpan-Ganzi sedimentary and basement rocks (Enkelmann et al., 2007; Hu et al., 2022b). Consequently, we suggest that the duration of pluton emplacement is approximately 10 Myr, from ~210 Ma to 200 Ma. This timeframe (~10 Myr) is also consistent with geochronologic studies of other intrusive suites (e.g., Coleman et al., 2004; Miles and Woodcock, 2018). However, unlike those long-lived granites (e.g., Miles and Woodcock, 2018), the Ke'eryin pluton contains no mafic enclaves. We speculate that a high geothermal gradient may prolong magmatism without contributions from high-temperature mantle-derived magma. The older zircons (>220–210 Ma) in Ke'eryin granites reported by Deschamps et al. (2017) may be records of magmatic activity at deep crustal levels before emplacement (c.f., Miles and Woodcock, 2018). For the Taiyanghe pluton, previous studies have generally proposed that the

TG and TD were emplaced at ~207 Ma (Yuan et al., 2010; Yue et al., 2019, 2018), whereas Deschamps et al. (2017) suggested a protracted emplacement history (~40 Myr) from 239 Ma to 202 Ma with a peak at ~207 Ma. As mentioned above, we speculate that the older zircon ages obtained by Deschamps et al. (2017) could be related to deep crustal magmatic processes. In consideration of our new zircon U-Pb dating results (Fig. 3), we propose that the Taiyanghe pluton was emplaced during ~212–207 Ma.

4.2. Petrogenesis of the Ke'eryin-Taiyanghe plutons

4.2.1. Ke'eryin pluton

Previous studies have suggested that the Ke'eryin pluton is compositionally homogeneous (i.e. S-type granite, Deschamps et al., 2017). However, we propose that the KTMG magma was extracted from the KBG magma via fractional crystallization and subsequently assimilated more sedimentary materials. Although the Sr-Nd-Hf isotopic

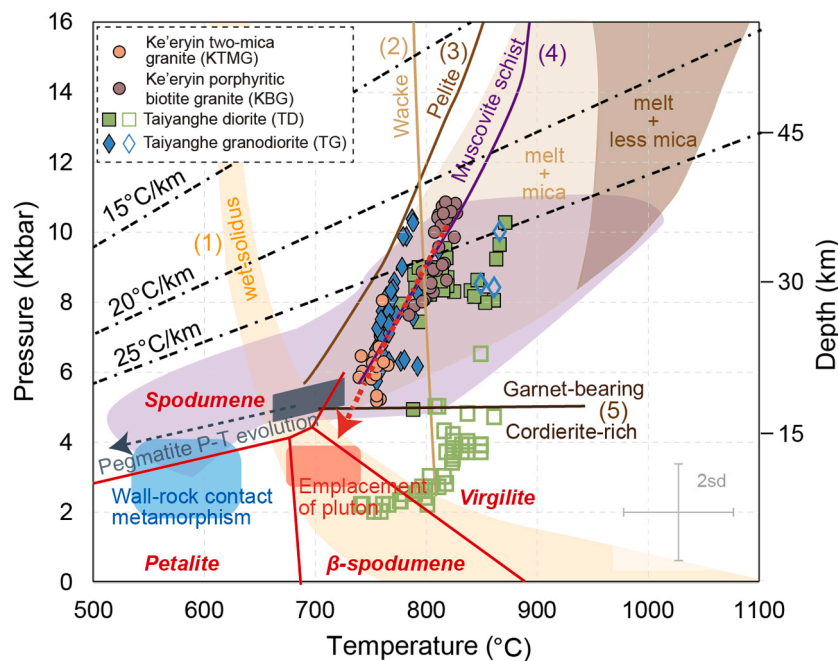


Fig. 7. The calculated P–T conditions for the magmatic rocks from the Ke’eryin-Taiyanghe plutons. The data points represent P–T conditions calculated from mineral thermobarometry (solid symbols: biotite; empty symbols: amphibole). Error bar (2sd) of P–T estimation uncertainty is shown. References for curves or fields of melting and mineral stability are presented in the Supplementary Figures. The P–T evolutionary trend of pegmatite is after Fei et al. (2021). The emplacement condition of pluton is after Deschamps et al. (2017). The wall-rock contact metamorphism in Ke’eryin-Taiyanghe area is after Zhao et al. (2019).

compositions of the KTMG and KBG are similar (Fig. 4a, c, and 5e), zircons from the KTMG exhibit higher $\delta^{18}\text{O}$ values, generally $> 11\text{‰}$ (Fig. 4b). Oxygen isotopic composition can reflect the addition of sedimentary material to the magma, because low-temperature water-rock interactions during sedimentary processes can increase the $\delta^{18}\text{O}$ value of rocks (Bindeman, 2008). Deschamps et al. (2017) also mentioned that abundant metasedimentary xenoliths were observed in the KTMG. Therefore, the KTMG records a greater contribution from sedimentary materials in compared to that of the KBG. A few zircons from the KTMG display lower $\delta^{18}\text{O}$ values, comparable to those in the KBG (Fig. 4b), and are interpreted as antecrysts derived from the KBG. The KBG has lower SiO_2 and higher Ba and Sr contents compared to those of the KTMG and it exhibits an increase in Sr at a constant Ba/Sr ratio (Fig. 5g), which may be attributed to the accumulation of K-feldspar. Plagioclase in the KBG exhibits complex core-to-rim zoning, characterized by an initial increase in An content, followed by a decrease and a subsequent increase (Fig. S3). This pattern is interpreted as reflecting one or more magma recharge events. Therefore, we propose that the KBG represents an early cumulate phase.

As mentioned above, the KTMG magma was contaminated by sedimentary materials, resulting in their elevated zircon $\delta^{18}\text{O}$ values (Bindeman, 2008). Geochemical modeling indicates that 20–30% crustal assimilation can reproduce the oxygen isotopic compositions of the KTMG when the lowest $\delta^{18}\text{O}$ value is used to represent the initial magma composition (Fig. 4d). This degree of crustal assimilation can also explain the higher zircon P and Li contents in the KTMG (Fig. 6b). The Li content of metasedimentary rocks from the Songpan-Ganzi terrane (~ 60 ppm) is approximately three times higher than that of the average upper crust (~ 20 ppm) (Hu et al., 2022a; Rudnick and Gao, 2003), promoting more efficient Li enrichment in the melt (Fig. S5). In addition, higher rates of assimilation, which can be achieved through increasing wall-rock temperature (DePaolo, 1981), would further enhance Li enrichment (Fig. S5). The abundance of inherited zircon cores in the KTMG and the absence of zircon cores in the KBG suggest that these zircons were most likely assimilated from the wall-rock after the crystallization of cumulated phases (Fig. S1). The higher SiO_2 and lower Ba

and Sr contents, coupled with lower Eu/Eu^* ratios in the KTMG, indicate that these rocks have also undergone fractional crystallization of K-feldspar and biotite (Fig. 5). During magmatic fractionation, Li, Cs, and Ta contents will increase (Fig. 5h and i). Notably, the Li content in zircons with $U < 2000$ ppm (12.0–142 ppm, average = 55 ppm) is high relative to that of the whole-rock compositions (62–262 ppm, average = 125 ppm). Consequently, the apparent zircon/melt Li partition coefficients of 0.06 to 1.16 (average = 0.49) are significantly higher than the experimental partition coefficients of 0.015 to 0.15 at 700–900°C (Wang and Trail, 2022). This suggests that the KTMG zircon and whole-rock compositions are not in equilibrium (Fig. 6f). A high-Li melt has been proposed to have existed and been extracted to form Li-pegmatites, leaving behind a Li-depleted granite (Hu et al., 2024). We propose that the enrichment of Li in the Ke’eryin pluton was primarily achieved through magmatic fractionation and crustal assimilation. The KTMG represents the residual magma that underwent a Li-rich melt extraction event before final solidification.

As discussed by Li et al. (2021), all granitoid rocks in the Songpan-Ganzi terrane have undergone varying degrees of assimilation of local (meta)sedimentary rocks. Our data indicate that the contribution of sediments varies within a single pluton. The petrological and geochemical characteristics of the KBG indicate that it is primarily composed of early crystallized phases with only a limited degree of crustal assimilation. Therefore, we focus on the KBG to assess the magma source. The Sr–Nd–O isotopic compositions of the KBG are more enriched than those of the western Yangtze Neoproterozoic mafic basement rocks (Fig. 4b and c; Zhao et al., 2018). We interpret this to indicate that the Songpan-Ganzi sedimentary rocks were already present in the source region of the KBG magmas prior to crustal melting. The P–T estimates for the KBG indicate that it originated at depths ≥ 40 km within the crust (Fig. 7), corresponding to the middle to lower crust (Hu et al., 2022b). We speculate that the Songpan-Ganzi sedimentary rocks may have been buried to such depths during the collision between the Yangtze Craton and the Songpan-Ganzi terrane (Li et al., 2021; Xu et al., 2020).

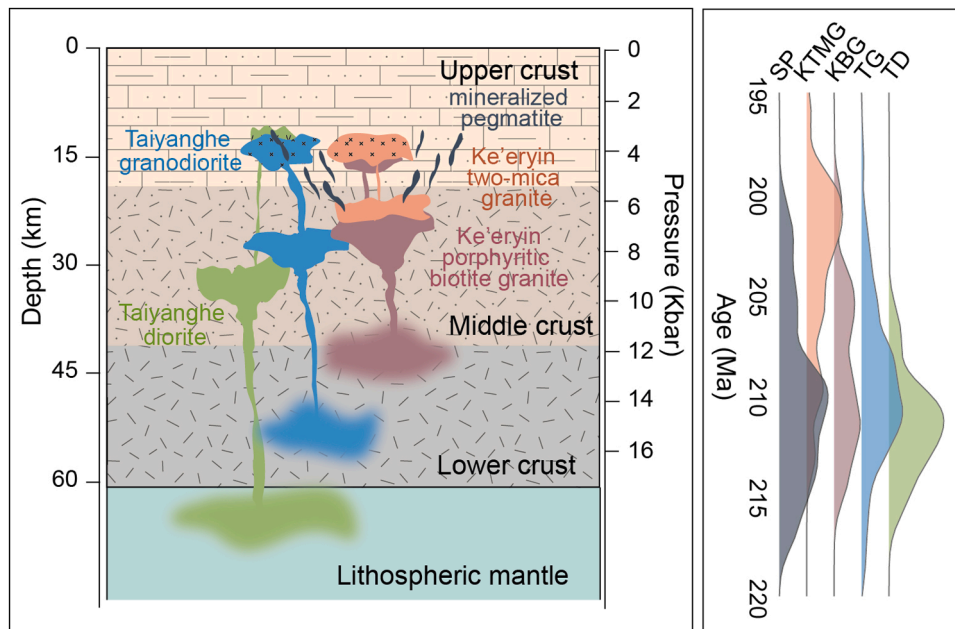


Fig. 8. Schematic crustal profiles and probability density plots of crystallization ages of the Ke'eryin-Taiyanghe plutons. The Taiyanghe diorite (TD) was formed first, which originated from partial melting of enriched lithospheric mantle. Then the Taiyanghe granodiorite (TG) was derived from partial melting of tholeiitic basaltic rocks of lower crust due to high temperatures. At the same time, partial melting of metasedimentary rocks and basaltic rocks in the middle to lower crust formed the Ke'eryin pluton. The porphyritic granite (KBG) represents a cumulate formed during fractional crystallization and the two-mica granite (KTMG) represents the residual melt after Li-rich melt extraction. The data sources for ages of Ke'eryin-Taiyanghe plutons and spodumene-bearing pegmatites (SP) are listed in the Supplementary Figures.

4.2.2. Taiyanghe pluton

Previous studies have suggested that the TD is composed primarily of residual cumulate phases, whereas the TG represents a more differentiated magma extracted from the same parental magma (Deschamps et al., 2017). Although TD and TG display similar Sr-Nd-Hf isotopic compositions (Fig. 4), their whole-rock and mineral compositional data display contrasting features (Figs. 5, S2, and S3), indicating that they may have undergone distinct magmatic evolutionary processes or originated from different sources.

The TG samples belong to the ferroan series, in contrast to the TD samples belonging to the magnesian series (Fig. 5d) (Frost et al., 2001). Furthermore, the amphibole and biotite compositions in the TG display alkaline signatures, which are distinct from those in the TD (Fig. S3). The MgO-rich amphibole and biotite from the TD could not have crystallized from a ferroan magma (Frost et al., 2001). Therefore, we propose that the TD and TG have distinct magmatic sources, with the TD originating from the partial melting of an enriched lithospheric mantle source. The variations in zircon Hf-O isotopic compositions and elevated $\delta^{18}\text{O}$ values in the TD are interpreted as reflecting crustal contamination during magma ascent and emplacement (Fig. 4c and d). The compositional zoning of plagioclase in the TD is interpreted to record episodes of magma recharge or injection (Fig. S3).

The Li content of the TD varies (~ 100 – 600 ppm) and is anomalously high (>500 ppm), exceeding that of the more evolved KTMG (Fig. 5h). This feature cannot be explained by partial melting or magmatic fractionation, given the limited variations in major element compositions (Kunz et al., 2022; Wu et al., 2020). One possible explanation is the diffusion of Li from adjacent spodumene-bearing pegmatites into the TD, as documented at Tin Mountain by Teng et al. (2006). However, Li diffusion would only affect adjacent wall-rocks (~ 30 – 50 m) and lead to an extremely light Li isotopic composition, which is inconsistent with the TD isotopic data ($\delta^7\text{Li} = -3.2$ – $+4.7$ ‰) (Li et al., 2021). Another potential explanation is the assimilation of metasedimentary rocks (Li et al., 2021). However, the crustal assimilation of a low-silica melt is unlikely to increase Li concentrations from 100 ppm to 600 ppm without

significantly affecting major elements. These TD samples exhibit a wide range of K/Rb ratios (~ 50 – 300), which are negatively correlated with Li content (Fig. 5i). Typically, such low K/Rb ratios are characteristic of highly fractionated granites or pegmatites (Ballouard et al., 2016), indicating that the TD may have been influenced by a Li-rich melt or fluid. However, pegmatitic fluids in this region display high Cs/Rb ratios with low Rb contents (Yuan et al., 2023) and the addition of such fluids will increase Cs while lowering Rb contents, which is inconsistent with the TD samples. Geochemical modeling indicates that the addition of only 0.5–1.0% of a pegmatitic melt can account for the observed compositional variations without significantly affecting major element concentrations (Fig. 5i). The disequilibrium between zircon Li content and whole-rock Li content (Fig. 6f) indicates that Li enrichment in the whole-rock may postdate zircon crystallization. However, in the absence of field or microscopic evidence for fluid-rock interaction (Fig. 2; Deschamps et al., 2017), we propose that Li enrichment likely occurred prior to magma crystallization.

The TG displays alkaline compositions similar to those of A-type granites and high Ba-Sr granites (Figs. 5, S2, and S3). However, its wide range of SiO_2 (~ 50 – 75 wt.%) and high Ba (>2000 ppm) concentrations, combined with a peraluminous feature, distinguish it from typical A-type and high Ba-Sr granites (Li et al., 2021; Zhang et al., 2007). These features are comparable to those of Sherman granite in North America, which has been interpreted as the product of partial melting of tholeiitic mafic rocks (Frost et al., 1999). In the Songpan-Ganzi terrane, minor tholeiitic mafic rocks are exposed in the southern part of the study area, representing part of the Emeishan basalts (Fig. 1a; Shellnutt, 2014). Some Emeishan basalts exhibit Sr-Nd isotopic compositions similar to those of the TG samples (Fig. 4c; Shellnutt, 2014). It is therefore possible that tholeiitic basaltic rocks in the deep crust underwent partial melting to generate the TG. Estimated temperatures (see Table S5 and S6) indicate that they have relatively high temperatures compared to those of other igneous rocks in the Ke'eryin-Taiyanghe plutons, which may support this hypothesis. Although the Emeishan basalts exhibit mantle-like oxygen isotopic signatures (Yao et al., 2019; Yu et al., 2017),

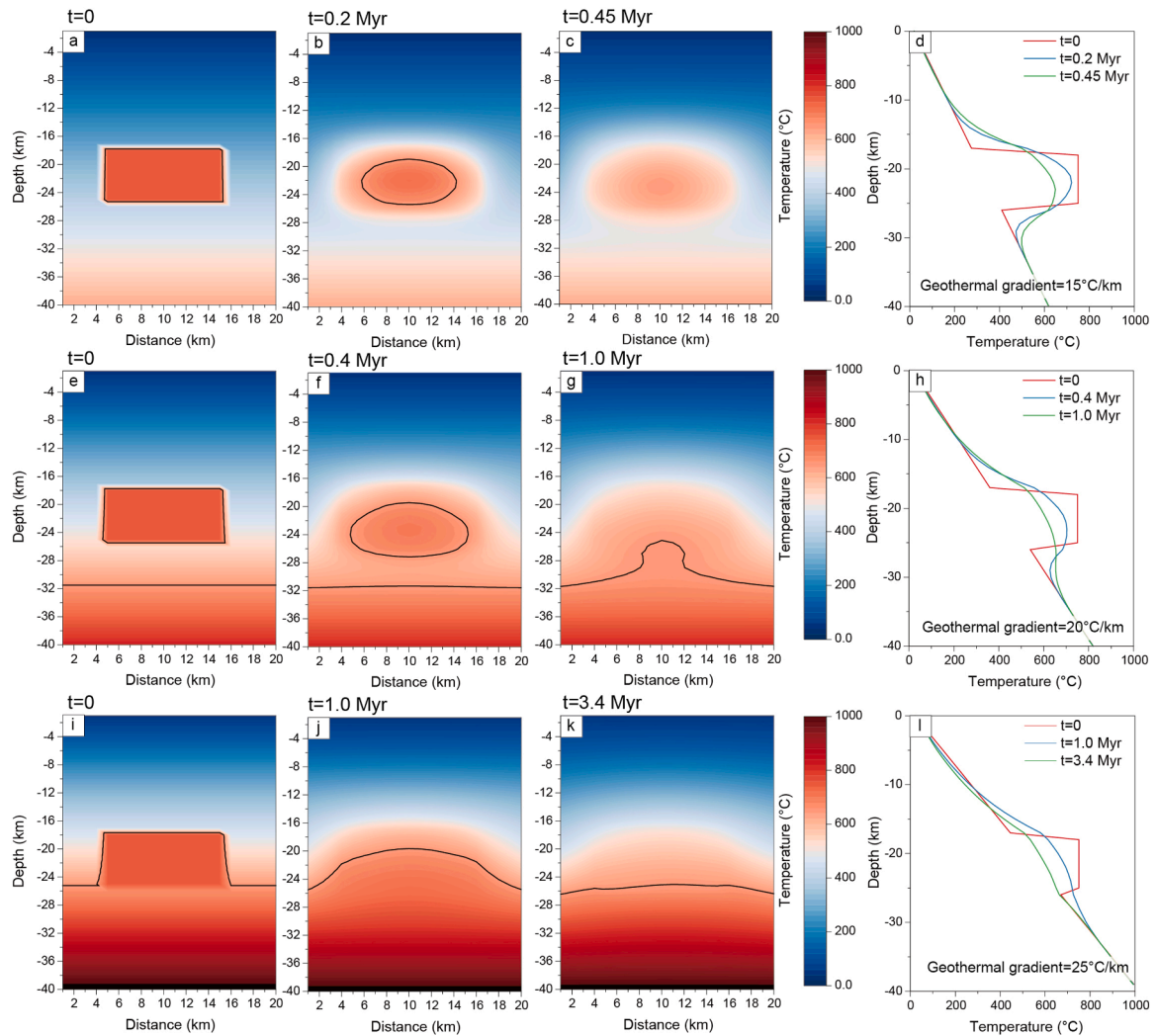


Fig. 9. Thermal modeling results for cooling of a magma body at different geothermal gradients. The modeling is conducted with HEAT 3D software (Wohletz et al., 1999). 2D crustal temperature profiles are illustrated at different times with geothermal gradients of 15°C/km (a-d), 20°C/km (e-h), and 25°C/km (i-l). The solid black line indicates a temperature of 650°C, representative of a completely crystallized granitic magma. The initial temperature of the granitic magma is set at 750°C with a thermal conductivity of 1.5 W/mK, a heat capacity of 1100 J/kgK, and a density of 2400 kg/m³. In the model, the upper crust is composed of metasedimentary rocks from 0 to 18 km depth with a thermal conductivity of 3.0 W/mK, a heat capacity of 980 J/kgK, and a density of 2650 kg/m³. The lower crust is composed of amphibolite from 18 to 40 km depth with a thermal conductivity of 2.6 W/mK, a heat capacity of 980 J/kgK, and a density of 2900 kg/m³. References for the crustal-related parameters mentioned above are shown in the Supplementary Figures.

in contrast to the TG samples (Fig. 4d), the constant Sr-O isotopic compositions of the TG samples (Fig. 4d and 5e) indicate that crustal assimilation was insignificant. Therefore, we suggest that the high $\delta^{18}\text{O}$ values and peraluminous signatures of the TG may be inherited from their source, which was likely a mixture of tholeiitic basalts and metasedimentary rocks. Collectively, the Taiyanghe pluton represents magmas derived from high-temperature partial melting of the lithospheric mantle and continental crust, implying a potentially elevated geothermal gradient.

4.3. Relationship between granite plutons and mineralized pegmatite

Traditionally, coeval granitic plutons exposed near Li-pegmatites have been considered the parental rocks of the pegmatites (Černý et al., 1985; Trueman and Černý, 1982). However, this interpretation has been challenged by studies showing that granitic plutons are not always spatially or genetically associated with Li-pegmatites (Knoll et al., 2023; Simmons et al., 2016). Furthermore, a recent drilling investigation of the Jiajika deposit indicated that the exposed “granite pluton” at the center of the pegmatite field is, in fact, a granitic sheet (Xu

et al., 2023).

Although the spodumene-bearing pegmatites in the study area are generally interpreted as having formed through magmatic fractionation of the KTMG (Li et al., 2023, 2022; Yan et al., 2024), some studies have proposed that they instead originated from anatexis of metasedimentary rocks, based on (1) age differences between the KTMG and pegmatites; and (2) discontinuities in the temperature and salinity ranges of fluid inclusions between the KTMG and the spodumene-bearing pegmatite (Fei et al., 2021, 2020). However, the Li mineralization (~210–200 Ma) is essentially contemporaneous with magmatism of the Ke’eryin pluton (~210–200 Ma) (Table S1). In addition, the high Li content in zircons from the KTMG indicates the presence of a Li-rich granitic melt during magmatic evolution (Fig. 6f; Hu et al., 2024). Therefore, we propose that the spodumene-bearing pegmatites are genetically related to the Ke’eryin pluton.

The Li-pegmatites could have been derived from a deeper magma chamber. The thermobarometric data for the Ke’eryin granites and Li-mineralized pegmatites (Fei et al., 2021) indicate that the pegmatites were extracted from a parental magma at ~5–6 kbar, deeper than the final emplacement depth of the KTMG (~3–4 kbar) (Deschamps et al.,

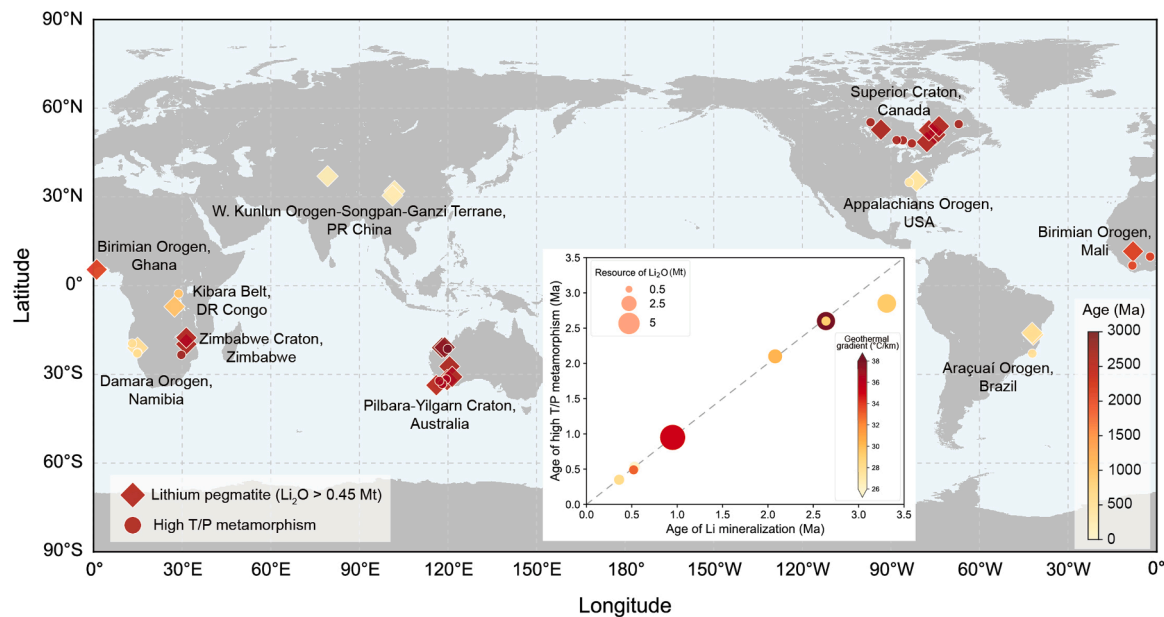


Fig. 10. Locations and ages of large Li-pegmatite deposits ($\text{Li}_2\text{O} > 0.45 \text{ Mt}$) around the world and ages of high T/P metamorphism near the Li-pegmatites. Diamond symbols are large Li-pegmatite deposits and circle symbols are high T/P metamorphism. The inset shows the correlation between the age of Li mineralization and the age of high T/P metamorphism in different orogens/cratons. Large Li pegmatites are commonly associated with the high T/P metamorphism in space and time. The detailed data are listed in Table S8.

2017). We suggest that the Li-rich pegmatitic melt was extracted from this deep magma chamber and migrated along structural weaknesses or faults, intruding into the Triassic metasedimentary strata and the Taiyanghe pluton (Fig. 8; e.g., Silva et al., 2023). Following this extraction event, the residual parental magma likely continued to differentiate through fractional crystallization, ultimately producing the KTMG, which was emplaced into the metasedimentary strata at $\sim 3\text{--}4 \text{ kbar}$ and 700°C (Figs. 7 and 8; Deschamps et al., 2017; Zhao et al., 2019). The absence of temperature or compositional gradients in fluid inclusions between the KTMG and the spodumene-bearing pegmatites is therefore a natural outcome of this magmatic evolution. Although a multi-stage partial melting model may also account for the compositional gaps (Koopmans et al., 2023), the absence of pre-existing Li-rich granites in the Songpan-Ganzi terrane (e.g., Zhu et al., 2019), along with the distinct isotopic compositions of older granites compared to Triassic Li-related granites, suggests that this model is not applicable in this region. We suggest that the geochemical composition of the parental granites may reflect a residual melt following Li-rich melt extraction rather than the initial melt, which help account for some of the observed compositional gaps between the granites and rare-metal pegmatites (e.g., Chakraborty and Upadhyay, 2020).

4.4. Importance of high geothermal gradients on lithium mineralization

In general, studies on Li mineralization have predominantly focused on highly fractionated granites and pegmatites, often overlooking the mafic and intermediate rocks surrounding the pegmatites (partly due to their absence), because mafic rocks are typically considered petrogenetically unrelated to Li-pegmatites. However, the presence of mafic rocks coeval with the Li-pegmatites may indicate elevated geothermal gradients, which could facilitate crustal melting and assimilation (c.f., Karlstrom et al., 2010; Lee et al., 2014). For instance, the melting conditions proposed by Koopmans et al. (2023) ($\sim 750\text{--}850^\circ\text{C}$, $\sim 3\text{--}8 \text{ kbar}$) suggest that high geothermal gradients are essential for producing Li-rich pegmatitic melts through a multi-stage partial melting process. In the study area, the Taiyanghe pluton appears geochemically and isotopically unrelated to the Li-pegmatites, however, their crystallization ages and spatial location (Figs. 1 and 8) indicate a close spatiotemporal

relationship. The formation of mantle-derived magma (TD) and high-temperature crustal-derived magma (TG) suggests that geothermal gradients were elevated during the Late Triassic. This elevated heat flow could help explain the Li enrichment in the KTMG through crustal assimilation, despite its relatively shallow emplacement depth, which is typically considered relatively cool and unfavorable for assimilation (Fig. 6).

Another important aspect of high geothermal gradients is their role in inhibiting the rapid cooling of granitic magmas, thereby allowing extended periods for magmatic fractionation (Jagoutz, 2014). To assess this effect, we performed thermal modeling to evaluate how geothermal gradients influence the lifespan of a magma chamber. The results indicate that the lifespan of a magma chamber increases exponentially with increasing geothermal gradient (Fig. 9). For example, a magma chamber of $10 \text{ km} \times 7 \text{ km}$ cools from 750°C to 650°C in $\sim 0.5 \text{ Myr}$ under a normal geothermal gradient (15°C/km) at mid-crustal depth ($\sim 20 \text{ km}$), however, this cooling period extends to $\sim 3.5 \text{ Myr}$ under an elevated geothermal gradient (25°C/km). Prolonging the duration over which magma can undergo fractionation and assimilation may promote the enrichment of rare-metal elements in magma (e.g., Li). Therefore, we suggest that elevated geothermal gradients could be a crucial physical condition for the formation of Li-pegmatites, whether through magmatic fractionation and assimilation or via multi-stage partial melting.

Indeed, many rare-metal pegmatites worldwide formed during the Archean, a period characterized by higher geothermal gradients compared to those of the Phanerozoic (Brown and Johnson, 2019; McCauley and Bradley, 2014). Moreover, the formation of rare-metal pegmatites is generally coeval with the assembly of supercontinents, especially during the late stages (McCauley and Bradley, 2014), which correspond to extensional periods characterized by high geothermal gradients in orogenic evolution (Harris et al., 1986). The spatiotemporal distribution of Li-bearing pegmatites is also similar to that of orogenic gold deposits (McCauley and Bradley, 2014), whose formation is linked to lithosphere-scale thermal anomalies (Goldfarb et al., 2001). A global compilation reveals a temporal and spatial correlation between known large Li-pegmatite deposits ($>0.45 \text{ Mt}$ of Li_2O) and regions with high T/P metamorphism ($>25^\circ\text{C/km}$) (Fig. 10; Brown and Johnson, 2019). Although high temperature granulites themselves do not host

Li-pegmatites due to their formation at deeper crustal levels, this global pattern underscores the crucial role of high geothermal gradients in generating major Li-pegmatite deposits. While not essential for all Li-pegmatites, high geothermal gradients may significantly enhance the formation of large Li-pegmatite deposits by extending magmatic evolution, promoting fractionation and assimilation, or triggering partial melting of Li-rich sources.

5. Conclusions

The Ke'eryin pluton is primarily composed of KBG and KTMG, which crystallized at ~209 Ma and ~202 Ma, respectively. It was derived from partial melting of metasedimentary rocks and basaltic basement rocks in the middle to lower crust. The KBG represents early crystallized cumulate phases, while the KTMG reflects the composition of a residual melt following the extraction of a Li-rich melt, indicating that the Ke'eryin pluton underwent significant magmatic fractionation. The composition of KTMG, therefore, does not represent the parental magma of the Li-pegmatites. Together with the positive correlation between zircon Li content and zircon oxygen isotopic compositions, we suggest that the assimilation of Li-rich metasedimentary rocks, coupled with magmatic fractionation, was the primary process responsible for the enrichment of rare-metal elements (e.g., Li) in the Ke'eryin pluton.

The Taiyanghe pluton is mainly composed of TD and TG, which crystallized at ~210–212 Ma. The TD formed through partial melting of enriched lithospheric mantle and its anomalously high Li content may reflect the limited addition of Li-rich pegmatitic melt. The TG originated from high-temperature partial melting of tholeiitic basaltic rock (likely Emeishan basalts) and metasedimentary rocks in the lower crust, indicative of high geothermal gradients during the Late Triassic.

Globally, large Li-pegmatite deposits are generally associated with regions of high T/P metamorphism, both temporally and spatially. Together with our case study, we propose that elevated geothermal gradients, which can facilitate crustal assimilation and prolong magmatic fractionation, may be a key factor in the formation of Li deposits.

CRediT authorship contribution statement

Fangyang Hu: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition. **Mihai N. Ducea:** Writing – review & editing. **James B. Chapman:** Writing – review & editing. **Lei Yang:** Writing – review & editing, Writing – original draft, Investigation. **Guohui Chen:** Writing – review & editing, Investigation. **Chunli Guo:** Writing – review & editing, Funding acquisition. **Fu-Yuan Wu:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

All the data for this research are available in the Supplementary Material.

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