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Apatite U-Pb dating of kimberlite: a feasibility study from South China

Zhang J[1,2] , Wang H[3] , He D[4]

[1] *Guizhou Geological Survey, Guiyang, China, jiaweizhang@live.cn*
[2] *Guizhou University, Guiyang, China*
[3] *Yanduzhongshi Geological Analysis Laboratory Ltd., Beijing, China, 282894878@qq.com*
[4] *Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China, hedefeng@mail.gyig.ac.cn*

Introduction

Kimberlite dating poses significant challenges due to its silica-poor, volatile-rich, strongly altered, and hybrid characteristics (Mitchell et al., 2019). Existing radiometric dating methods include Rb-Sr and ^{40}Ar-^{39}Ar dating of phlogopite, as well as U-Pb dating of mantle zircon and groundmass perovskite (Heaman et al., 2019). However, these methods are either analytically complex or limited by the scarcity of suitable mineral geochronometers.

Apatite emerges as a dependable geochronometer for several reasons. First, it is readily available in various magmatic rocks. Second, it is enriched in U and Th contents. Third, its U-Pb isotopic system exhibits closure temperatures up to 550 ℃ (Chew and Spikings, 2015). Recent advancements inU-Pb geochronology allow precise measurements of low U (<3 ppm) and high common Pb proportions (>50%) in apatite (Chew et al., 2011). Apatite sometimes outperforms zircon in the highly evolved volatile-rich granitic system (e.g., Feng et al., 2023) and the mafic system (e.g., Li et al., 2021). Despite apatite's lower U-Pb isotopic closure temperature compared to zircon, reference apatites from the Qinghu quartz monzonite in Zhejiang Province, China (this study), and the McClure Mountain syenite in Colorado, USA (Schoene and Bowring, 2006), yield identical U-Pb apatite age as zircon did in such slowly cooling granitic system. These findings suggest that apatite may be suitable for dating the emplacement age of rapidly cooling, ultrabasic magmatic rocks like kimberlite. In this contribution, we systematically conducted U-Pb dating on seven apatite samples from kimberlite and related rocks in South China. These apatite U-Pb ages are compared with phlogopite ^{40}Ar-^{39}Arages from the same dike, aiming to demonstrate that LA-ICP-MS U-Pb dating of apatite provides a robust method for constraining the emplacement age ofkimberlite.

Major findings

The largest dike swarm of kimberlite, lamproite, and lamprophyre in South China is prominently exposed in eastern Guizhou Province. Over 730 dikes intruded into Late Tonian to Late Cambrian strata, their emplacement controlled by east-west-trending regional faults (Zhang et al., 2023). To ascertain the emplacement ages and patterns of these dikes, we measured apatite U-Pb isotopic ratios of the certified reference samples and the diamond-bearing kimberlite and related rocksat the Yanduzhongshi Geological Analysis Laboratory Ltd., utilizing an optimized NWR193 laser ablation system and PlasmaQuant MS.Age calculations involved plotting uncorrected data on the Tera-Wasserburg concordia diagram to determine lower intercept ages. When samples exhibited a concentrated distribution in common Pb/radiogenic Pb ratios,common Pb corrections are applied by carefully estimating initial Pb isotopic compositions. Notably, certified reference apatites—such as Otter Lake apatite and MAD2 apatite—

yielded Tera-Wasserburg lower-intercepted ages of 907.5±2.9 Ma (n=57, MSWD=1.2) and 476.8±1.4 Ma (n=66, MSWD=1.3), respectively. These ages closely align with their recommended values (Figure 1), suggesting U-Pb ages of these reference apatites have been accurately and precisely determined.

Apatite U-Pb dating results from seven kimberlite and related rock samples in South China reveal ages ranging between 492 and 441 Ma (Table 1). To validate accuracy and precision, we analyzed phlogopite phenocrysts (>250 μm) from the Baifen dike using the ^{40}Ar-^{39}Ar method. The ^{40}Ar-^{39}Ar plateau ages for certified reference materials GA-1550 biotite and FCs sanidine closely match their recommended values (98.79±0.96 Ma and 28.02±0.28 Ma, respectively, Renne et al., 1998).

Our apatite sample from the Baifen dike yielded a U-Pb age of 466±13 Ma (n=46, MSWD=1.5), while two phlogopite samples yielded identical ^{40}Ar-^{39}Ar plateau ages of 451±3 Ma (2σ, n=13/15, MSWD=0.74) and 453±3 Ma (2σ, n=12/14, MSWD=0.68). These consistent ages, obtained from different minerals and isotopic systems within the same dike across two different institutes, underscore the robustness of apatite U-Pb dating for constraining kimberlite emplacement age.

Table 1 LA-ICP-MS apatite U-Pb age of kimberlite and related rocks inSouth China.

Sample	Rock type*	Locality	Lower intercept age (Ma)	n	MSWD
19MP	Kimberlite	Maping	492±12	55	1.2
20XT	Lamprophyre	Xitou	484±8	26	2.5
20BF	Lamproite	Baifen	466±13	46	1.5
20PY	Lamproite	Pingyang	455±7	40	1.2
20DP-2	Kimberlite	Daping	449±12	38	2.3
20DT	Kimberlite	Datang	448±11	40	0.83
20NC	Lamprophyre	Nancen	441±7	37	0.6

*The inference of the rock types involves plotting the geochemical compositions on the Al_2O_3-K_2O-MgO classification diagram, which applies to lamprophyres, lamproites, and kimberlites (Bergman, 1987).

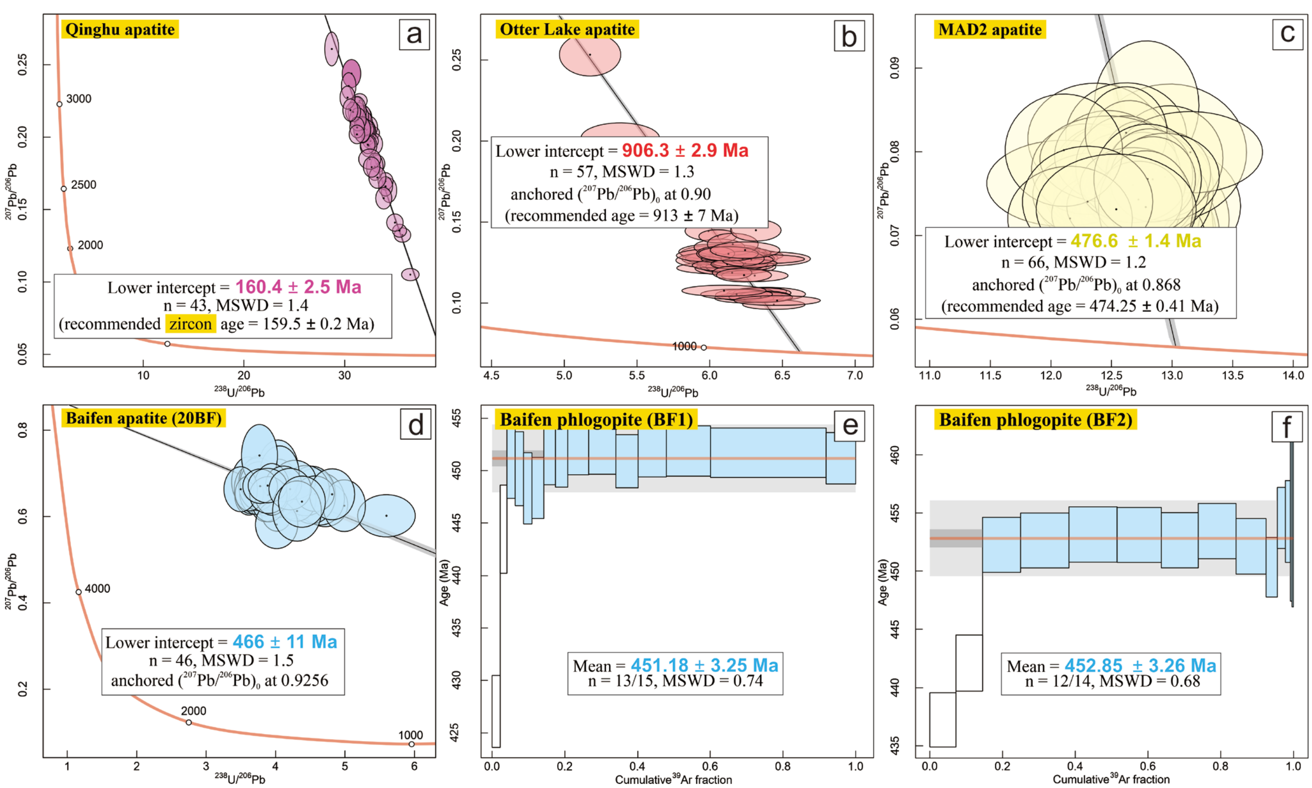

Figure 1. Tera-Wasserburg plotsfor(a) Qinghu quartz monzonite apatite (this study; recommended zircon age sourced from Li et al., 2013); (b) reference Otter Lake apatite (recommended apatite age sourced from Barfod et al., 2005); (c) reference MAD2 apatite (recommended apatite age sourced from Thomson et al., 2012); and (d) Baifen apatite sample (initial $^{207}Pb/^{206}Pb$ value derived from the measured whole-rock $^{207}Pb/^{206}Pb$ ratio by Zhang et al., 2023).(e) $^{40}Ar/^{39}Ar$ age of the Baifen phlogopite sample (BF1) (Zhang et al., 2023); (f) $^{40}Ar/^{39}Ar$ age of the Baifen phlogopite sample (BF2) (Zhang et al., 2023).

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