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Editorial

Dating Kimberlite Using Apatite U-Pb Geochronology: A Case Study from Diamond-Bearing Dikes in South China

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Kimberlite, one of the deepest known magmatic rocks on Earth, offers valuable glimpses into the deep mantle composition (Woodhead et al., 2019), craton structure (Gardiner et al., 2020), global geodynamic variation (Tappe et al., 2018), and diamond formation (Giuliani et al., 2023). The accurate determination of the emplacement of this special rock is crucial for revealing such information. However, dating kimberlite is challenging due to its silica-poor, volatile-rich, strongly altered, and hybrid nature (Mitchell et al., 2019).

Zircon is unsuitable for dating kimberlite and related rocks due to its preference for crystallizing in intermediate to felsic melts (Gervasoni et al., 2016) rather than silica-poor ones. Even if present, zircon is prone to Pb loss through hydrothermal alteration (Zi et al., 2022) in a volatile-rich system like kimberlitic magmas. Reliable radiometric dating methods for kimberlite emplacement age include U-Pb dating of groundmass perovskite and mantle zircon, Rb-Sr dating of phlogopite macrocryst, and ^{40}Ar-^{39}Ar dating of groundmass phlogopite (Heaman et al., 2019), (U-Th)/He dating of zircon and perovskite (Stanley and Flowers, 2016), and U-Pb dating of desilicification rim of zircon xenocryst (Melnik et al., 2022), etc. However, these methods are hindered by the strict requirements of rare mineral geochronometers and complex analytical procedures, limiting their widespread applications in kimberlite geochronology.

Apatite, a calcium phosphate accessory mineral that is ubiquitous in all igneous rocks, presents a viable alternative. Apatite fission-track and apatite (U-Th)/He analyses were successfully employed in the reconstruction of the low-temperature thermal history in the range from 60 to 120 °C (Ding, 2023; Chew et al., 2011). Apatite possesses a moderate closure temperature for U-Pb isotopic system, it therefore represents an easily accessible and highly reliable geochronometer for recording thermal histories within a temperature range of 350–550 °C (Chew and Spikings, 2015). Apatite demonstrates a significant advantage and yields better U-Pb age results compared to zircon in some extreme scenarios, such as in highly evolved volatile-rich granitic system (e.g., Feng et al., 2023) and mafic system (e.g., Li et al., 2021). Recent advances in *in-situ* U-Pb geochronology allow for accurate and precise measurements of low U (<3 ppm) and high common Pb proportion (>50%) apatite, using suitable certified references and a careful choice of common Pb composition (Chew et al., 2011). Although the U-Pb isotopic closure temperature of apatite is lower than that of zircon, and the apatite U-Pb age typically represents the cooling age rather than crystallization age as zircon did, many examples manifest that both minerals extracted from the same rocks may yield identical U-Pb ages in some magmatic systems. One noteworthy example is the Qinghu quartz monzonite in Zhejiang Province, China. This rock exhibits an apatite U-Pb age of 160.4 ± 2.5 Ma (Figure 1a and ESM Table S1) consistent with its recommended zircon U-Pb age of 159.5 ± 0.2 Ma (Li et al., 2013). Another illustration involves the McClure Mountain syenite in Colorado, USA, where its apatite U-Pb age (523.51 ± 1.47 Ma) coincides with the recommended zircon U-Pb age (523.98 ± 0.12 Ma) (Schoene and Bowring, 2006). The above evidence suggests that no Pb diffusion occurs in apatite sometimes, even in a slowly cooling magmatic system. In terms of kimberlite, a product of a high-velocity magma that can erupt from the mantle to the surface within days (Russell et al., 2019), the apatite U-Pb age appears theoretically suitable for dating emplacement age of these rapidly cooling magmatic rocks. Li et al. (2016) briefly reported the results of SIMS U-Pb dating of apatite from Zhenyuan lamproite in South China, but the application of LA-ICP-MS U-Pb dating of apatite for constraining the emplacement age of kimberlite has been poorly documented. This work conducted a systematical U-Pb dating of seven apatite samples from the kimberlite and related rocks in South China. The obtained apatite U-Pb ages are comparable with phlogopite ^{40}Ar-^{39}Ar dating results from the same dike, which demonstrates that the LA-ICP-MS U-Pb dating of apatite can be a powerful approach to constrain the emplacement age of kimberlite and related rocks.

The largest kimberlite-lamproite-lamprophyre dike swarm

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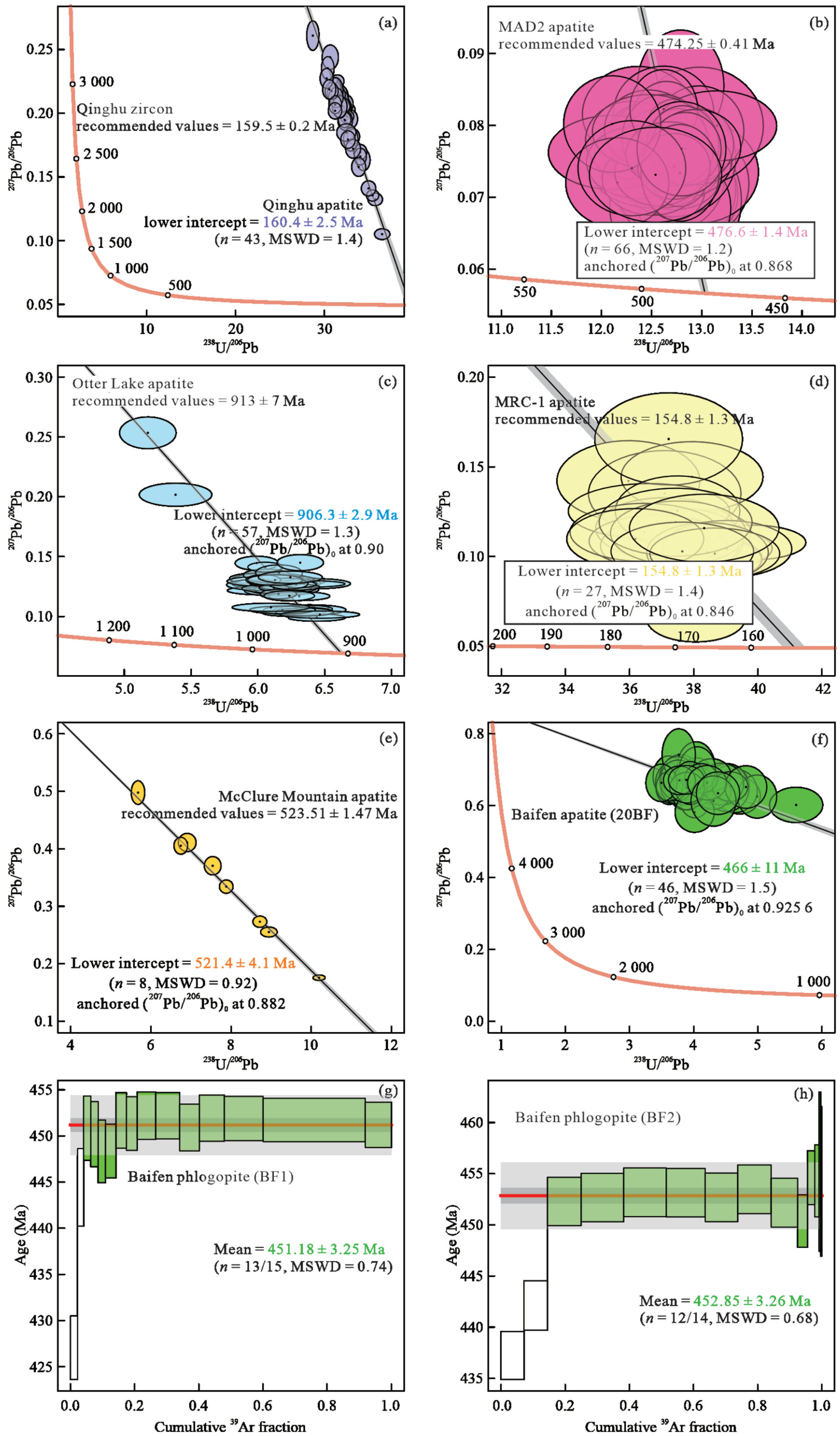

Figure 1. Tera-Wasserburg plots of LA-ICP-MS data for apatite. (a) U-Pb age of the Qinghu quartz monzonite apatite (this study); the recommended zircon age of the Qinghu quartz monzonite is from Li et al. (2013); (b) U-Pb age of the reference MAD2 apatite; the recommended apatite age is from Thomson et al. (2012); (c) U-Pb age of the reference Otter Lake apatite; the recommended apatite age is from Barfod et al. (2005); (d) U-Pb age of the MRC-1 apatite; the recommended apatite age is from Apen et al. (2022); (e) U-Pb age of the reference McClure Mountain apatite; the recommended apatite age is from Schoene and Bowring (2006); (f) U-Pb age of the Baifen apatite sample (20BF); the initial $^{207}Pb/^{206}Pb$ value is derived from the measured whole-rock $^{207}Pb/^{206}Pb$ ratio (Zhang et al., 2023); (g) $^{40}Ar/^{39}Ar$ age of the Baifen phlogopite sample (BF1) (Zhang et al., 2023); (h) $^{40}Ar/^{39}Ar$ age of the Baifen phlogopite sample (BF2) (Zhang et al., 2023).

Table 1 LA-ICP-MS U-Pb apatite age results for kimberlite and related rocks from Guizhou, 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

*Rock type is inferred based on their geochemical compositions (unpublished) and plotting them on the Al_2O_3-K_2O-MgO geochemical classification diagram (not shown) of lamprophyres, lamproites, and kimberlites (Bergman, 1987).

in South China is outcropped at eastern Guizhou Province. These dikes intruded into Late Tonian to Late Cambrian strata and were controlled by the EW-trending regional faults. The emplacement ages and patterns of this rock suite remain poorly constrained. Here, the apatite U-Pb isotopic ratios of the kimberlite and related rocks in this region were measured at the Yanduzhongshi Geological Analysis Laboratory Ltd. through an optimized NWR193 laser ablation system and PlasmaQuant MS. Analytical procedures were described by Zhang et al. (2023). Age calculations involved plotting the uncorrected data on the Tera-Wasserburg concordia diagram to obtain the lower intercept ages. Common Pb corrections were applied when samples showed a concentrated distribution in common Pb/radiogenic Pb ratios, with a careful estimate of initial Pb isotopic compositions.

The Pb isotopic data of the Qinghu apatite are first reported in this article and listed in ESM Table S1, other data have previously been published (Zhang et al., 2023). Certified references, including MAD2 apatite, Otter Lake apatite, MRC-1 apatite, and McClure Mountain apatite, yielded Tera-Wasserburg lower-intercepted ages of 476.6 ± 1.4 Ma (n = 66, MSWD = 1.2), 906.3 ± 2.9 Ma (n = 57, MSWD = 1.3), 154.8 ± 1.3 Ma (n = 27, MSWD = 1.4), and 521.4 ± 4.1 Ma (n = 8, MSWD = 0.92), respectively, which are consistent with their recommended values (474.25 ± 0.41, 913 ± 7, 153.3 ± 0.2, 523.51 ± 1.47 Ma, respectively) within uncertainties (Figures 1b–1e), indicating that U-Pb ages of these reference apatites have been accurately and precisely determined. Seven kimberlite and related rocks yielded apatite U-Pb ages between 492 and 441 Ma with small errors (Table 1), consistent with previously reported whole-rock Sm-Nd and Rb-Sr ages (Fang et al., 2002), and SIMS rutile and apatite U-Pb ages (Li et al., 2016). Among them, the mica-rich Baifen dike yielded a U-Pb age of 466 ± 13 Ma (Figure 1f).

To evaluate the accuracy and precision of apatite U-Pb dating results, two phlogopite phenocryst samples (>250 μm) were separated from the Baifen dike and dated simultaneously and independently by using ^{40}Ar-^{39}Ar method at the State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences. Certified references GA-1550 biotite and FCs sanidine yielded ^{40}Ar-^{39}Ar plateau ages of 98.73 ± 0.61 Ma (2σ, including 97% of the ^{39}Ar, MSWD = 0.71) and 27.97 ± 0.17 Ma (2σ, including 100% of the ^{39}Ar, MSWD = 0.33) (Figures 1g–1h), respectively, which are coincident with their recommended values (98.79 ± 0.96 Ma for GA-1550 and 28.02 ± 0.28 Ma for FCs, Renne et al., 1998). Two phlogopite samples from the Baifen dike yielded identical ^{40}Ar-^{39}Ar plateau ages of 451 ± 3 Ma (2σ, including 96% of the ^{39}Ar, n = 13/15, MSWD = 0.74) and 453 ± 3 Ma (2σ, including 86% of the ^{39}Ar, n = 12/14, MSWD = 0.68), confirming the validity of the ^{40}Ar-^{39}Ar isotopic system of the Baifen dike. Furthermore, the apatite U-Pb age and phlogopite ^{40}Ar-^{39}Ar ages, obtained from two different minerals and isotopic systems within the same dike at two different institutes, were broadly concordant within analytical uncertainty. Our case study therefore affirms that the apatite LA-ICP-MS U-Pb dating can be a promising and robust approach for constraining the emplacement age of kimberlite.

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Conflict of Interest

The authors declare that they have no conflict of interest.

REFERENCES CITED

Apen, F. E., Wall, C. J., Cottle, J. M., et al., 2022. Apatites for Destruction: Reference Apatites from Morocco and Brazil for U-Pb Petrochronology and Nd and Sr Isotope Geochemistry. *Chemical Geology*, 590: 120689. https://doi.org/10.1016/j.chemgeo.2021.120689

Barfod, G. H., Krogstad, E. J., Frei, R., et al., 2005. Lu-Hf and PbSL Geochronology of Apatites from Proterozoic Terranes: A First Look at Lu-Hf Isotopic Closure in Metamorphic Apatite. *Geochimica et Cosmochimica Acta*, 69(7): 1847–1859. https://doi. org/10.1016/j. gca. 2004.09.014

Bergman, S. C., 1987. Lamproites and Other Potassium-Rich Igneous Rocks: A Review of Their Occurrence, Mineralogy and Geochemistry. *Geological Society of London Special Publications*, 30(1): 103–190. https://doi.org/10.1144/gsl.sp.1987.030.01.08

Chew, D. M., Spikings, R. A., 2015. Geochronology and Thermochronology

Using Apatite: Time and Temperature, Lower Crust to Surface. *Elements*, 11(3): 189–194. https://doi.org/10.2113/gselements.11.3.189

Chew, D. M., Sylvester, P. J., Tubrett, M. N., 2011. U-Pb and Th-Pb Dating of Apatite by LA-ICPMS. *Chemical Geology*, 280(1/2): 200 – 216. https://doi.org/10.1016/j.chemgeo.2010.11.010

Ding, R. X., 2023. Low Temperature Thermal History Reconstruction Based on Apatite Fission-Track Length Distribution and Apatite U-Th/He Age Using Low-*T* Thermo. *Journal of Earth Science*, 34(3): 717–725. https://doi.org/10.1007/s12583-020-1071-x

Fang, W., Hu, R., Su, W., et al., 2002. Emplacement Ages of Lamproites in Zhenyuan Area, Guizhou Providence, China. *Chinese Science Bulletin*, 47(10): 307–312 (in Chinese)

Feng, Y. Z., Lu, W. J., Xiao, B., et al., 2023. Apatite Geochronology and Geochemistry of Gucheng Granites: Implications for Petrogenesis and REE Metallogenesis in South China. *Ore Geology Reviews*, 163: 105791. https://doi.org/10.1016/j.oregeorev.2023.105791

Gardiner, N. J., Kirkland, C. L., Hollis, J. A., et al., 2020. North Atlantic Craton Architecture Revealed by Kimberlite-Hosted Crustal Zircons. *Earth and Planetary Science Letters*, 534: 116091. https://doi.org/10.1016/j.epsl.2020.116091

Gervasoni, F., Klemme, S., Rocha-Júnior, E. R. V., et al., 2016. Zircon Saturation in Silicate Melts: A New and Improved Model for Aluminous and Alkaline Melts. *Contributions to Mineralogy and Petrology*, 171(3): 21. https://doi.org/10.1007/s00410-016-1227-y

Giuliani, A., Phillips, D., Pearson, D. G., et al., 2023. Diamond Preservation in the Lithospheric Mantle Recorded by Olivine in Kimberlites. *Nature Communications*, 14: 6999. https://doi.org/10.1038/s41467-023-42888-x

Heaman, L. M., Phillips, D., Pearson, G., 2019. Dating Kimberlites: Methods and Emplacement Patterns through Time. *Elements*, 15(6): 399–404. https://doi.org/10.2138/gselements.15.6.399

Li, L. L., Shi, Y. R., Anderson, J. L., et al., 2021. Dating Mafic Magmatism by Integrating Baddeleyite, Zircon and Apatite U-Pb Geochronology: A Case Study of Proterozoic Mafic Dykes/Sills in the North China Craton. *Lithos*, 380/381: 105820. https://doi.org/10.1016/j.lithos.2020.105820

Li, Q. L., Li, X. H., Wu, F. Y., et al., 2016. Accessary Minerals SIMS U-Th-Pb Dating for Kimberlite and Lamproite. *Acta Geologica Sinica—English Edition*, 90(Suppl. 1): 74–75. https://doi.org/10.1111/1755-6724.12896

Li, X. H., Tang, G. Q., Gong, B., et al., 2013. Qinghu Zircon: A Working Reference for Microbeam Analysis of U-Pb Age and Hf and O Isotopes. *Chinese Science Bulletin*, 58(36): 4647–4654. https://doi.org/10.1007/s11434-013-5932-x

Melnik, A. E., Li, Q. L., Korolev, N. M., et al., 2022. Desilicification Rims of Zircon Xenocrysts Record the Timing of Kimberlite Emplacement. *Journal of Geophysical Research* (*Solid Earth*), 127(9): e2022JB024482. https://doi.org/10.1029/2022jb024482

Mitchell, R. H., Giuliani, A., O'Brien, H., 2019. What is a Kimberlite? Petrology and Mineralogy of Hypabyssal Kimberlites. *Elements*, 15(6): 381–386. https://doi.org/10.2138/gselements.15.6.381

Renne, P. R., Swisher, C. C., Deino, A. L., et al., 1998. Intercalibration of Standards, Absolute Ages and Uncertainties in $^{40}Ar/^{39}Ar$ Dating. *Chemical Geology*, 145(1/2): 117–152. https://doi.org/10.1016/s0009-2541(97)00159-9

Russell, J. K., Sparks, R. S. J., Kavanagh, J. L., 2019. Kimberlite Volcanology: Transport, Ascent, and Eruption. *Elements*, 15(6): 405–410. https://doi.org/10.2138/gselements.15.6.405

Schoene, B., Bowring, S. A., 2006. U-Pb Systematics of the McClure Mountain Syenite: Thermochronological Constraints on the Age of the $^{40}Ar/^{39}Ar$ Standard MMHB. *Contributions to Mineralogy and Petrology*, 151(5): 615–630. https://doi.org/10.1007/s00410-006-0077-4

Stanley, J. R., Flowers, R. M., 2016. Dating Kimberlite Emplacement with Zircon and Perovskite (U-Th)/He Geochronology. *Geochemistry*, *Geophysics*, *Geosystems*, 17(11): 4517–4533. https://doi.org/10.1002/2016gc006519

Tappe, S., Smart, K., Torsvik, T., et al., 2018. Geodynamics of Kimberlites on a Cooling Earth: Clues to Plate Tectonic Evolution and Deep Volatile Cycles. *Earth and Planetary Science Letters*, 484: 1–14. https://doi.org/10.1016/j.epsl.2017.12.013

Thomson, S. N., Gehrels, G. E., Ruiz, J., et al., 2012. Routine Low-Damage Apatite U-Pb Dating Using Laser Ablation-Multicollector-ICPMS. *Geochemistry*, *Geophysics*, *Geosystems*, 13(2): Q0AA21. https://doi.org/10.1029/2011gc003928

Woodhead, J., Hergt, J., Giuliani, A., et al., 2019. Kimberlites Reveal 2.5-Billion-Year Evolution of a Deep, Isolated Mantle Reservoir. *Nature*, 573: 578–581. https://doi.org/10.1038/s41586-019-1574-8

Zhang, J. W., Santosh, M., Zhu, Y. H., et al., 2023. Constraining the Timing of Deep Magmatic Pulses from Diamondiferous Kimberlite and Related Rocks in the South China Continent and Implications for Diamond Exploration. *Ore Geology Reviews*, 154: 105328. https://doi.org/10.1016/j.oregeorev.2023.105328

Zi, J. W., Rasmussen, B., Muhling, J. R., et al., 2022. *In situ* U-Pb and Geochemical Evidence for Ancient Pb-Loss during Hydrothermal Alteration Producing Apparent Young Concordant Zircon Dates in Older Tuffs. *Geochimica et Cosmochimica Acta*, 320: 324–338. https://doi.org/10.1016/j.gca.2021.11.038