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说明：该文档仅作为测试方法的主要描述，不可直接用于文章的写作。另，测试方法仍需根据实际测试情况进行相应的更改（如标样不一致、测试条件不一致等）。其他同位素的测试方法描述文档还在完善。

## Sr同位素分析方法说明

The in-situ apatite Sr isotope measurements were conducted on a *Nu Plasma III* MC-ICP-MS (Nu Instruments) that was attached to a RESOlution-155 ArF193-nm laser ablation system (Australian Scientific Instruments) at State Key laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences. Apatite was ablated in a mixture of helium (350 ml/min) and nitrogen (2 ml/min) atmosphere using the following parameters: 30 s baseline time, 40 s ablation time, 60-104 μm spot size, 6 Hz repetition rate and 6 J/cm2 energy density. The analytical and interference correction protocol follows the method described in Ramos et al. (2004) and was fully addressed in Gao and Zhou (2013). One in-house standard consisting of a modern-day coral every five samples and two apatite standards (including AP1 and MAD) every thirty unknown samples were treated as quality control. The measured 87Sr/86Sr ratio for the apatite standard AP1 was 0.71133 ± 0.00004 (n = 12), which was identical to the recommended value (AP1: 0.71136 ± 0.00008) (Yang et al., 2014).

Modern Coral: 0.709172 (Hodell et al., 1990)

MAD: 0.71180±0.00003 (Yang et al.,2014)

Otter Lake: 0.70419±0.00003, (Yang et al.,2014)

AP1: 0.71136 ± 0.00008 (Yang et al., 2014)

AP2: 0.72655±0.00002 (Yang et al.,2009)

References:

Hodell, D. A., Mead, G. A., Mueller, P. A. (1990). Variation in the strontium isotopic composition of seawater (8 Ma to present): Implications for chemical weathering rates and dissolved fluxes to the oceans. Chemical Geology: Isotope Geoscience section, 80(4), 291-307.

Gao, J. F., Zhou, M. F. (2013). Generation and evolution of siliceous high magnesium basaltic magmas in the formation of the Permian Huangshandong intrusion (Xinjiang, NW China). *Lithos*, *162*, 128-139.

Ramos, F. C., Wolff, J. A., Tollstrup, D. L. (2004). Measuring 87Sr/86Sr variations in minerals and groundmass from basalts using LA-MC-ICPMS. *Chemical Geology*, *211*(1-2), 135-158.

Yang Y.H., Wu F.Y., Xie L.W., Yang J.H., Zhang Y.B.  (2009). In-situ Sr isotopic measurement of natural geological samples by LA-MC-ICP-MS. Acta Petrologica Sinica, 25(12), 3431-3441. (in Chinese with English abstract)

Yang, Y. H., Wu, F. Y., Yang, J. H., Chew, D. M., Xie, L. W., Chu, Z. Y., ... Huang, C. (2014). Sr and Nd isotopic compositions of apatite reference materials used in U–Th–Pb geochronology. Chemical Geology, 385, 35-55.

延伸材料（不用附在文章上，这是有关校正的，若评论人问到相关问题，可从中选择出作答：

The instrumental mass bias for Sr isotopes was corrected using an exponential law function and a 86Sr/88Sr of 0.1194.

The interferences were corrected in the following order: (1) Kr+ gas blank, (2) doubly charged rare earth elements (REE; Er2+ and Yb2+, corrected by measuring m/z corresponding to 166Er2+, and 171Yb2+ and 173Yb2+ at half mass, with the following natural ratios used: 176Yb/173Yb = 0.79107, 174Yb/173Yb = 1.97334, 172Yb/173Yb = 1.353378, 170Er/166Er = 0.44421, 168Er/166Er = 0.797084, 164Er/166Er = 0.047873, 164Dy/163Dy = 1.13173), (4) 87Rb+ on 87Sr+ by measuring 85Rb+, applying mass bias based on measured 86Sr/88Sr and assuming the exponential law as with Sr.

## Nd同位素方法说明

The in-situ apatite Nd isotope measurements were conducted on a *Nu Plasma III* MC-ICP-MS (Nu Instruments) that was attached to a RESOlution-155 ArF193-nm laser ablation system (Australian Scientific Instruments) at State Key laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences. Apatite was ablated in a mixture of helium (350 ml/min) and nitrogen (2 ml/min) atmosphere using the following parameters: 30 s baseline time, 40 s ablation time, 60-104 μm spot size, 6 Hz repetition rate and 6 J/cm2 energy density. The interference of 144Sm on 144Nd was derived from the 147Sm intensity with a natural 144Sm/147Sm ratio of 0.205484(Isnard et al., 2005). The mass bias factor of Sm was calculated from the measured isotopic ratio of 147Sm/149Sm and its true value 1.08680 (Isnard et al., 2005）. The mass bias of 143Nd/144Nd was normalized to 146Nd/144Nd = 0.7129 with an exponential law. One apatite standard Durango every five samples and other two apatite standards (AP1 and MAD) every thirty unknown samples were treated as quality control. The measured 43Nd/144Nd ratio for the apatite standard AP1 was 0.512342 ± 0.000014 (n = 12), which was identical to the recommended value (AP1: 0.512352 ± 0.000024) (Yang et al., 2014).

Durango: 0.512483±0.000004 (Foster and Vance, 2006)

MAD: 0.511322±0.000053 (Yang et al.,2014)

Otter Lake: 0.512940±0.000009, (Yang et al.,2014)

AP1:0.512352 ± 0.000024 (Yang et al., 2014)

AP2: 0.511007±0.000030 (Yang et al.,2014)

References:

Foster, G. L., Vance, D. (2006). In situ Nd isotopic analysis of geological materials by laser ablation MC-ICP-MS. *Journal of Analytical Atomic Spectrometry*, *21*(3), 288-296.

Isnard, H., Brennetot, R., Caussignac, C., Caussignac, N., Chartier, F. (2005). Investigations for determination of Gd and Sm isotopic compositions in spent nuclear fuels samples by MC ICPMS. *International Journal of Mass Spectrometry*, *246*(1-3), 66-73.

Yang, Y. H., Wu, F. Y., Yang, J. H., Chew, D. M., Xie, L. W., Chu, Z. Y., Huang, C. (2014). Sr and Nd isotopic compositions of apatite reference materials used in U–Th–Pb geochronology. Chemical Geology, 385, 35-55.

## S同位素分析方法说明

The in-situ Sulfur isotope measurements were performed on a Nu Plasma III MC-ICP-MS (Nu Instruments) that was attached to a RESOlution-155 ArF193-nm laser ablation system (Australian Scientific Instruments) at State Key laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences. The mass separation was calculated as 0.3333 in the analyses. The instrument was operated in pseudo-medium resolution mode (Millet et al., 2012) to resolve polyatomic interferences from 16O–16Ofor 32S and 16O–18O for 34S, adjusting the source slit to medium (0.05 mm) in conjunction with using the alpha slit. Sulfide was ablated in a mixture of helium (350 ml/min) and nitrogen (2 ml/min) atmosphere using the following parameters: 20 s baseline time, 40 s ablation time, 40s wash time, 40-60 μm spot size, 5 Hz repetition rate and 2-3 J/cm2 energy density. All analyses followed standard sample bracketing procedures of three samples bracketed by a pyrite pressed powder tablet (PSPT-2) (Bao et al., 2017, Chen et al., 2017). Two in-house standards consisting of nature pyrite crystals (SB-1 from Shangbao W-Sn deposit and HYC-1 from Huayangchuan Nb-U-REE deposit, China) every five unknown samples were treated as quality control. The measured δ34SV-CDT for the standard were 16.57‰ (n=12)for SB-1 and -5.76‰ for HYC-1(n=12), which was identical to the recommended value (16.57‰ for SB-1 and -5.76‰ for HYC-1) (IRMS).

Bao, Z.A., Chen, L., Zong, C. L., Yuan, H.L., Chen, K.Y., Dai, M.L., 2017. Development of pressed sulfide powder tablets for in situ sulfur and lead isotope measurement using LA-MC-ICP-MS. International Journal of Mass Spectrometry: 421, 255-262,

Chen, L., Yuan, H.L., Chen, K.Y., Bao, Z.A., Zhu, L.M., Liang, P., 2019. In situ sulfur isotope analysis by laser ablation MC-ICPMS and a case study of the Erlihe Zn-Pb ore deposit, Qinling orogenic belt, Central China. Journal of Asian Earth Sciences: 176, 325-336.

Millet, M.A., Baker, J.A., Payne, C.E., 2012. Ultra-precise stable Fe isotope measurements by high resolution multiple-collector inductively coupled plasma mass spectrometry with a 57Fe–58Fe double spike. Chem. Geol. 304–305, 18–25.

黄铜矿：

All analyses followed standard sample bracketing procedures of three samples bracketed by a chalcopyrite pressed powder tablet (PSPT-2) (Bao et al., 2017, Chen et al., 2017). One in-house standards consisting of a nature chalcopyrite crystal (BLP-1 from Sudbury Cu-Ni deposits, Canada) every five unknown samples were treated as quality control. The measured δ34SV-CDT for the standard were 4.18‰ (n=12), which was identical to the recommended value (4.17‰) (IRMS).

## 锆石Hf同位素分析方法说明

Hafnium isotopic ratios of zircon were conducted by LA-MC-ICP-MS at State Key laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences. Australian Scientific Instruments RESOlution-LR laser-ablation system and Nu Instruments *Nu Plasma III* MC-ICP-MS (Wrexham, Wales, UK) were combined for the experiments. The 193 nm ArF excimer laser, homogenized by a set of beam delivery systems, was focused on zircon surface with fluence of 6.0J/cm2. Ablation protocol employed a spot diameter of 40 um at 6 Hz repetition rate for 40 seconds (equating to 240 pulses). Helium was applied as carrier gas to efficiently transport aerosol to MC-ICP-MS. Five standard zircons (including GJ-1, 91500, Plešovice, Mud Tank, Penglai) every thirty unknown samples and one standard zircon (Penglai) every five samples were treated as quality control.

Mass bias effects on Hf were corrected using an exponential law and a true value for 179Hf/177Hf of 0.7325 (Patchett et al., 1981). Correction for isobaric interference of 176Lu on and 176Yb on 176Hf was corrected by using 176Yb/173Yb = 0.7962 and 176Lu/175Lu = 0.02655 (Vervoort et al., 2004) with an exponential-law mass bias correction assuming 173Yb/171Yb ratio of 1.129197 (Vervoort et al., 2004).

GJ-1

207Pb/206Pb 608.5±0.4 Ma

206Pb/238U 599.8±4.5 Ma (ID-TIMS, Jackson et al., 2004)

Hf 0.282 008 ± 25 (2SD) (侯可军 2007-岩石学报23, 2595)

Hf 0.282 012 (袁洪林 2008-ChemGeol 247, 100)

91500

207Pb/206Pb 1065.4±0.6 Ma

206Pb/238U 1062.4±0.8 Ma (ID-TIMS, Wiedenbeck et al, 1995)

Hf 0.282 307 ± 31 (2SD) (吴福元 2006-ChemGeol 234, 105)

Hf 0.282 309 (袁洪林 2008-ChemGeol 247, 100)

Plešovice

206Pb/238U 337.13±0.37 Ma (ID-TIMS, Sláma et al., 2008)

Hf 0.282 482±13 (2SD) (Sláma et al., 2008)

Mud Tank

206Pb/238U 732±5 Ma (ID-TIMS, Black and Gulson, 1978)

Hf 0.282 504±0.000044 (Woodhead and Hergt, 2005)

Hf 0.282 523±0.000043 (Griffin et al., 2006)

Hf 0.282 513 (袁洪林 2008-ChemGeol 247, 100)

Penglai 蓬莱

206Pb/238U 4.4±0.1 Ma (ID-TIMS, 李献华, 2010-GGR)

Hf 0.282 906 ±10 (2SD) (李献华, 2010-GGR)

Qinghu 清湖

206Pb/238U 159.5±0.2 Ma (ID-TIMS, 李献华, 2009-Geo3)

Hf 0.283 002±0.000004 (李献华，2013-科学通报)

Wu, F.Y., Yang, Y.H., Xie, L.W., Yang, J.H., Xu, P., 2006. Hf isotopic compositions of the standard zircons and baddeleyites used in U-Pb geochronology. Chemical Geology, 234, 105-126.

Yuan, H.L., Gao, S., Dai, M.N., Zong, C.L., Günther, D., Fontaine, G.H., Liu, X.M. and Diwu, C.R. 2008. Simultaneous determinations of U-Pb age, Hf isotopes and trace element compositions of zircon by excimer laser-ablation quadrupole and multiple-collector ICP-MS. Chemical Geology 247, 100-118.

Li, X.H., Long, W.G., Li, Q.L., Liu, Y., Zheng, Y.F., Yang, Y.H., Chamberlain, K.R., Wan, D.F., Guo, C.H., Wang, X.C., Tao, H., 2010. Penglai zircon megacrysts: a potential new working reference material for microbeam determination of Hf-O isotopes and U-Pb ages. Geostandards and Geoanalytical Research, 34, 117-134.

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