

ANALYTICAL METHODS

Scanning electron microscope (SEM)

The samples were investigated by backscattered electron (BSE) and cathodoluminescence (CL) imagings, and energy dispersive X-ray spectroscopy (EDS) element mappings. These investigations were conducted by using a JSM-7800F field emission scanning electron microscope (FE-SEM) equipped with a TEAM Apollo XL energy disperse spectroscope and a Gatan Mono CL4 detector at the State key Laboratory of Ore Deposit Geochemistry (SKLOGD), Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China. The accelerating voltages for BSE and CL imaging were operated at 20 kV and 10 kV, respectively, while the beam currents for both were 10 nA.

Electron microprobe analysis (EPMA)

Major element compositions of apatite, calcite, phengite and chlorite were determined with a JEOL JXA-8530F field emission electron probe microanalyzer at the State key Laboratory of Ore Deposit Geochemistry (SKLOGD), Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China. A current of 10 nA and a focused beam of 1-10 μm at an accelerating voltage of 25 kV were generally used for these minerals. Standards used for analyses of apatite include apatite for Ca, F, P, La, Ce and Nd, monazite for Pr, Sm and Th, tugtupite for Cl, kaersutite for Fe, Na, Si and Al, rhodenite for Mn, anhydrite for Sr and S, benitoite for Ba. The standards used for analyses of calcite include calcite for Ca, tugtupite for Cl, rhodenite for Mn, dolomite

for Mg, apatite for F, celestite for Sr, kaersutite for Fe, and monazite for La and Ce. The standards used for analyses of phengite include biotite for K, Si, Al, Mg and Fe, tugtupite for Cl, Kaersutite for Ca, Ti, Na and Mn, chlorite for Cr and Ni, and apatite for F. The standards used for analyses of chlorite include Kaersutite for K, Ca, Ti, Na and Mn, tugtupite for Cl, chlorite for Cr, Si, Al, Mg, Fe and Ni, and apatite for F. The limits of detection for these measured elements are 50 to 200 ppm.

In-situ trace element analysis by LA-ICP-MS

Trace element compositions of apatite and calcite were determined by a Photon Machines Excimer 193nm laser ablation system coupled with an Agilent 7700x at the FocuMS Laboratory, Nanjing, China. Helium was used as a carrier gas and argon was used as the make-up gas mixed with the carrier gas via a T-connector before entering the ICP. Analyses of apatite and calcite were performed at 6 Hz repetition rate with beam diameters of 10 and 40 μm , respectively, and included a background acquisition of approximately 20 seconds for a gas blank, followed by data acquisition of 40 seconds from the samples. For apatite analyses, element contents were calibrated against external standard NIST 610, every five analyses were followed by two analyses of external standard NIST 610 to correct time-dependent drift of sensitivity and mass discrimination. On the other hand, standards NIST 610 and 612 were used as external calibration standards for calcite analyses, which were analyzed twice after eight analyses of samples. Calcium, which was obtained by EPMA, was used as the internal standard for the analyses of both apatite and calcite.

In-situ Sr and Nd isotopic analyses by LA-MC-ICP-MS

In situ Sr and Nd isotopic analyses of apatite were conducted on 80-100- μm -thick polished section, using a Nu Plasma III MC-ICP-MS (Nu Instruments) that was attached to a RESolution-155 ArF193-nm laser ablation system at the State Key laboratory of Ore Deposit Geochemistry (SKLOG), Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China. The analytical protocol for in situ Sr isotope analyses follows the method described in Ramos et al. (2004) and Gao and Zhou (2013). 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; 40-60 μm spot size; 6 Hz repetition rate; 6 J/cm² energy density. The analytical accuracy was evaluated with repeated analyses of a modern-day coral and two apatite standards (AP1 and MAD) after five and thirty unknown samples, respectively. The measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the apatite standard AP1 was 0.71133 ± 0.00004 ($n = 12$), agreeing well with the recommended value (0.71136 ± 0.00008) (Yang et al., 2014). On the other hand, the analytical accuracy for in-situ Nd isotopic analyses was evaluated with repeated analyses of one apatite (Durango) and two apatite (AP1 and MAD) standards after five and every thirty unknown samples, respectively. The analytical protocol for in situ Nd isotope analyses follows the method described in Foster and Vance (2006) and Yang et al. (2014). The measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratio for the apatite standard AP1 was 0.512342 ± 0.000014 ($n = 12$), which agrees well with the recommended value (0.512352 ± 0.000024 ; Yang et al., 2014). The isobaric

interference of ^{144}Sm on ^{144}Nd was derived from the ^{147}Sm intensity with a natural $^{144}\text{Sm}/^{147}\text{Sm}$ ratio of 0.205484 (Isnard et al., 2005). In order to correct for this interference, the mass bias factor of Sm was calculated from the measured isotopic ratio of $^{147}\text{Sm}/^{149}\text{Sm}$ and its true value 1.08680, followed by estimation of the Sm interference on mass 144 by using the measured ^{147}Sm intensity and natural $^{147}\text{Sm}/^{144}\text{Sm}$ ratio (Isnard et al., 2005). The interference-corrected $^{146}\text{Nd}/^{144}\text{Nd}$ ratio was normalized to 0.7219 to correct the Nd fractionation factor, and then the $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{145}\text{Nd}/^{144}\text{Nd}$ ratios were normalized by using the exponential law. The exponential law was used for calculating the $^{147}\text{Sm}/^{144}\text{Nd}$ after correcting for the isobaric interference of ^{144}Sm on ^{144}Nd , and then was externally calibrated against the $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of the standards.

In situ Sm-Nd isotopic analyses of monazite and bastnäsite were performed using a Neptune multi-collector (MC) ICP-MS, equipped with a Geolas 193 nm excimer laser ablation system at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS), Beijing, China. The detailed analytical procedures for in situ Nd isotope of monazite and bastnäsite were described by Liu et al. (2012) and Yang et al. (2019), respectively, and thus were briefly summarized here. The analyses of monazite were conducted on 80-100- μm -thick polished sections, with a spot size of 20 μm and a repetition rate of 4 Hz. Each spot analysis involved ~20 s of background data acquisition and ~40 s of sample data acquisition. After analyses of eight samples, two standards were analyzed for external calibration. The isobaric interference of ^{144}Sm on ^{144}Nd is significant and the detailed processes for the correction are available in Li et

al. (2018). The monazite standard Namaqua was used for the analyses of monazite (reference values: $^{147}\text{Sm}/^{144}\text{Nd} = 0.0977 \pm 0.0002$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.511896 \pm 0.000032$; Liu et al. 2012). For the Nd isotopic analyses of bastnäsite, a laser spot size of 24 μm was employed with a 6 Hz repetition rate. Each spot analysis involved ~ 60 s data acquisition with the laser fire on. Standards used for external calibration were analyzed twice after ten samples. The recently revised Sm isotopic abundances ($^{147}\text{Sm}/^{149}\text{Sm} = 1.08680$ and $^{144}\text{Sm}/^{149}\text{Sm} = 0.22332$) were adopted to correct the isobaric interference of ^{144}Sm on the ^{144}Nd signal. Firstly, the measured $^{147}\text{Sm}/^{149}\text{Sm}$ ratio was used for calculating the Sm fractionation factor, and the Sm interference on mass 144 was estimated by using measured ^{147}Sm intensity and natural $^{147}\text{Sm}/^{144}\text{Sm}$ ratio (4.866559). Secondly, the Nd fractionation factor was calculated by using the interference-corrected $^{146}\text{Nd}/^{144}\text{Nd}$ ratio, while the $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{145}\text{Nd}/^{144}\text{Nd}$ ratios were normalized by using the exponential law. Finally, $^{147}\text{Nd}/^{144}\text{Nd}$ ratios of unknown samples could be calculated by using the exponential law after correcting the isobaric interference of ^{144}Sm on ^{144}Nd . During the measurement sessions, the $^{147}\text{Sm}/^{144}\text{Nd}$ ratio was then “externally” calibrated against the $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of a K-9 reference material (Yang et al. 2013).

Microthermometric and Raman spectroscopic analyses

The microthermometric study of fluid inclusions was conducted on a Linkam THMSG 600 programmable heating-freezing stage mounted on a Leica microscope with a measurable temperature ranging from -196 to 600 $^{\circ}\text{C}$ at the State Key Laboratory

of Ore Deposit Geochemistry (SKLODG), Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China. The measurement was calibrated using the microthermometric behavior of synthetic fluid inclusions of known composition. For temperatures below 0 °C, the accuracy of the measurements was about ± 0.1 °C and for temperature above 200 °C, it was about ± 1 °C.

Room temperature Raman spectroscopic analyses of the compositions of the fluid inclusions were conducted on 120-150- μm -thick polished section, using a LabRAM HR Evolution equipped with an argon ion laser having a source of 532 nm at SKLODG. The scanning range for the spectra was set between 100 and 4000 cm^{-1} and the data accumulation time was 5-10 s for each scan; the laser beam width was set to be ~ 2 μm , and the spectral resolution is ~ 0.6 cm^{-1} .

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