

ANALYTICAL METHODS

Whole-rock major element compositions were obtained by X-ray fluorescence spectrometry (XRF) on fused glass disks using an AXIOS-Minerals spectrometer at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). The FeO content was analyzed using a chemical titration method, and the Fe₂O₃ was recalculated using total iron and FeO. The analytical uncertainties were generally within 3% (RSD), according to the analyses of the international reference materials GSR-1 and GSR-3 and duplicate analyses of the samples. Whole-rock trace element compositions were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) using a Finnigan MAT Element spectrometer at the IGGCAS. The accuracy and precision of the data were better than 5% for most trace elements, according to the measurements of GSR-1 and GSR-3 and replicate analyses of the samples.

Back-scattered electron (BSE) images were acquired using a Nova NanoSEM 450 field emission scanning electron microscope (FSEM) and a JEOL JXA-8100 electron microprobe (EMP) at the IGGCAS. Quantitative major element compositions of the minerals were acquired using the JEOL JXA-8100 EMP. The analyses were performed in wavelength-dispersion mode (WDS) with an acceleration voltage of 15 kV, a beam current of 10 nA, a beam diameter of 1 μm , and a count time of 10-30 s. Natural minerals and synthetic oxides were used as standards, and data corrections were carried out using the ZAF routine. The analytical uncertainties for most major oxides were <1.5%.

To examine the nature of TiO₂ phases, an HR800 confocal laser Raman spectrometer with an Ar⁺ ion laser (with a wavelength of 532 nm and an output power of 44 mW) was used at the IGGCAS. Monocrystalline silicon with a Raman shift of 520.7 cm⁻¹ was used as the calibration standard before measurement.

The trace element compositions of rutile and Fe-Ti oxides were analyzed in situ on polished thin sections by laser ablation (LA)-ICP-MS at the IGGCAS. The instrument included a 193-nm ArF excimer laser coupled with a single-collector quadrupole Agilent 7500a ICP-MS system. Helium was used as a carrier gas to minimize aerosol deposition around the ablation site and improve the transport efficiency of the ablated material. The output energy was 80 mJ and the energy density was 10 J/cm². The spot size diameter was 32 μm for rutile and 60 μm for Fe-Ti oxides. Acquisition time was approximately 20 s for the background and 40 s for the sample analysis. For both rutile and Fe-Ti oxide measurements, ⁴⁹Ti was used as an internal standard. The solute contents of TiO₂ in rutile were measured via in situ EMP analysis. However, the Fe-Ti oxides are composed of H-Ilm exsolution lamellae and the I-Hem matrix (see the section below). Therefore, the TiO₂ contents of the Fe-Ti oxides were calculated based on the measured compositions of H-Ilm and I-Hem (Appendix Table 4) in relative proportions determined by model analysis of their areas in the BSE images (Figs. 3f and 4d). The glass reference material NIST SRM 610 (Pearce et al. 1997), which was used for external calibration, was measured at the beginning and end of each analytical batch (~9 analyses). The trace element data were calculated using the program GLITTER 4.0 Online Interactive Data Reduction for LA-ICP-MS developed by GEMOC at Macquarie University. During each analytical batch, the international rutile standard R10 (courtesy of Dr. Qiuli Li) was repeatedly measured twice as an unknown sample. The trace element concentrations measured for the R10 standard relative to the NIST SRM 610 agreed well within error with the recommended values (Luvizotto et al. 2009). Duplicate analyses of the R10 standard suggested that the accuracy and reproducibility for the contents of high field strength elements (HFSEs: Nb, Ta, Zr, and Hf) and transition

metal elements (TMEs: Cr and V) were better than 10%.

The in situ Sr isotopes of epidote were analyzed using a Neptune multi-collector ICP-MS (MC-ICP-MS) equipped with a 193 nm ArF Excimer laser ablation system at the IGGCAS. The detailed instrument, analytical procedure, and calibration technique have been introduced by Yang et al. (2009, 2014) and Guo et al. (2014, 2016). In situ Sr isotopic data were acquired in static, multi-collector mode with a low resolution using nine Faraday collectors. The laser spot size was 60 μm . The repetition rate was 6-8 Hz and the energy density was 10 J/cm². An in-house apatite standard (AP1, ~2500 ppm Sr) and a coral standard (>1000 ppm Sr) were used to evaluate the reliabilities of the laser analyses. The average ⁸⁷Sr/⁸⁶Sr ratios of the AP1 (0.71136 ± 7 , 2SD, n = 12) and coral (0.70918 ± 7 , 2SD, n = 12) measured in this study are identical within analytical uncertainty to those obtained from the solution-mode MC-ICP-MS analysis (0.711370 ± 31 for AP1) and laser methods (0.71137 ± 7 for AP1 and 0.70918 ± 5 for coral) (Yang et al. 2009, 2014).

MINERAL COMPOSITIONS OF MUSCOVITE, CHLORITE, AMPHIBOLE, PLAGIOCLASE, AND APATITE

Muscovite, which coexists with the Rt-C and Ep-C in the veins, has Si contents of 3.04-3.06 pfu and Al contents of 2.7-2.8 pfu (Appendix Table 7).

Chlorite in the veins has high Mg# values [$= \text{Mg}/(\text{Mg} + \text{Fe}^{2+})$] of 0.57-0.65 and Si contents of 2.6-2.8 pfu (Appendix Table 7). The amphibole in the amphibolites is classified as pargasite according to Leake (1997). The pargasite has Si contents of 6.50-6.51 and Mg# values of 0.61-0.63 (Appendix Table 7). The F and Cl contents of muscovite, chlorite, and pargasite are all below the detection limits.

The plagioclase in the amphibolites and veins has a similar composition and is classified as oligoclase, with 77-85 mol% albite and 15-23 mol% anorthite (Appendix Table 7). The apatite in the veins has very high F (2.8-3.2 wt%) contents and low Cl (<0.1 wt%) contents (Appendix Table 7).

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