Supplementary Methods

Back-scattered electron (BSE) imaging and energy-dispersive X-ray spectroscopy (EDS) were conducted using a Hitachi S-3400N variable pressure Scanning Electron Microscope (SEM) at the Electron Microscope Unit, University of Hong Kong (HKU). Cathodoluminescence (CL) images were taken using a Hitachi S-2380N SEM at the Department of Earth Sciences, HKU. This helped characterize mineral textures and guide the following geochemical analyses. The elemental composition of baddeleyite and zircon was analyzed using a JEOL JXA 8100 electron microprobe at the State Key Laboratory of Continental Tectonics and Dynamics, Chinese Academy of Geological Sciences, Beijing. Operating conditions include an acceleration voltage of 15 kV, a beam current of 20 nA, a beam diameter of 1 μm and a counting time of 30 seconds for each element. Data correction was achieved by standard ZAF procedures. Natural minerals and synthetic glasses, from Astimex Standards and ZSC REE Set, respectively, were used as standards for elements Si, Ca, P, Y, Zr, La, Ce, Eu, Sm, Lu, Hf, Ti, and U. Peak time and off-peak time are 20 s and 10 s for major elements, and 60 s and 30 s for trace elements. A general analytical precision is ±1.5 %.

Rare earth elements (REE) analyses of zircon were conducted on polished thin sections and mineral separates mounts using a GeoLas 2005 laser ablation system with an Agilent 7700a ICP-MS at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (CUG), Wuhan. Trace elements analyses of diopside and garnet were carried out using a GeoLasPro 193-nm laser ablation system with an Agilent 7700e ICP-MS at the Chinese Academy of Sciences Key Laboratory of Crust-Mantle Materials and Environments, University of Science and Technology of China (USTC), Hefei. Detailed operating conditions for the laser ablation system and the ICP-MS instrument and data reduction are the same as description by Liu et al. (2010) in the CUG laboratory and He et al. (2015) in the USTC laboratory, respectively. For zircon analyses, laser pulses of 24 μm diameter ablated the surfaces of the sample for about 50 s after monitoring the gas blank for approximately 20 s. For diopside and garnet analyses, laser pulses of 60 μm diameter ablated the surfaces of the sample for about 40 s after monitoring the gas blank for 20 s. The generated aerosols were carried out by a helium carrier gas, and mixed with argon make-up gas via a T-connector before entering the ICP-MS instrument for acquisition of ion-signal intensities. Rare earth elements compositions of zircon were calibrated against NIST SRM 610 using Zr as an internal standard (Liu et al. 2010). Trace elements compositions of diopside and garnet were calibrated by multiple external reference materials (BHVO-2G, BCR-2G, BIR-1G, and NIST SRM 610) using Si as a normalizing element in a strategy of summed metal-oxide normalization (Liu et al. 2008).

Microthermometry studies for calcite from the retrograde skarn stage were carried out with a Linkam MDS 600 Heating–Freezing System at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou. Thermocouples were calibrated in the range of -196 ºC to 600 ºC using synthetic fluid inclusions. The precision of temperature measurement is ±0.1 ºC in the range of -100 ºC to 25 ºC, ±1 ºC in the range of 25–400 ºC, and ±2 ºC for temperature above 400 ºC. The heating rate was generally 0.2–5 ºC/min during the process of fluid inclusion testing, but reduced to 0.1 ºC/min near the freezing point, and 0.2–0.5 ºC/min near the homogenization temperature to record the phase transformation process accurately.

Zircon oxygen isotopes were measured using the Cameca IMS 1280HR SIMS at the Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS), Beijing. Detailed instrument configuration and analytical procedure was described by Li et al. (2010) and Tang et al. (2015). The Gaussian focused Cs^+ primary ion beam was accelerated at 10 kV, with an intensity of 1-2 nA and rastered over a 10 μm area. The spot is about 20 μm in diameter. The normal-incidence electron gun was used to compensate for sample charging during analysis with homogeneous electron density over a 100 μm oval area. Negative secondary ions were extracted with a -10 kV potential. The field aperture was set to 5000 μm, and the transfer-optics magnification was ~130. Energy slit width was 30 eV. The entrance slit width is ~120 μm. NMR controller was used to stabilize magnetic field. Oxygen isotopes were measured in multi-collector mode using two off-axis Faraday cups (FCs). One analysis takes ~3 min consisting of pre-sputtering (20 s), automatic beam centering (~60 s) and integration of oxygen isotopes signals (20 cycles×4 s, total 80 s). The intensity of ^{16}O was ~1.1×10^9 cps in one session and ~1.7×10^9 cps in another, for the difference of primary beam intensities in two sessions. Values of $\delta^{18}O$ are standardized to VSMOW and reported in standard per mil notation (Baertschi 1976). Penglai zircon (Li et al. 2010) was used as primary standard to correct instrument mass fractionation (IMF) as follows:

$$\left(\delta^{18}O\right)_M = \left(\frac{\left({}^{18}O/{}^{16}O\right)_M}{0.0020052} - 1\right)\times 1000(‰)$$

$$IMF = \left(\delta^{18}O\right)_{M(standard)} - \left(\delta^{18}O\right)_{VSMOW}$$

$$\delta^{18}O_{Sample} = \left(\delta^{18}O\right)_M + IMF$$

Multiple grains of Qinghu zircon standard (Li et al. 2013) were run as unknowns. The analytical uncertainties in two sessions are evaluated by standard deviation of measured $\delta^{18}O$ values of Penglai zircon in the same session, which were 0.20 ‰ (1SD, N=20) and 0.23 ‰ (1SD, N=10). Using Penglai as primary standard, the returned $\delta^{18}O$ values of Qinghu in two sessions were 5.61±0.22 ‰ (1SD, N=4) and 5.66±0.26 ‰ (1SD, N=10) (Supplementary Table S1), which were consistent with the recommended value (5.4±0.1 ‰, 1SD) within error.

Measurements of U, Th and Pb were conducted using the Cameca IMS-1280 SIMS at the Institute of Geology and Geophysics, CAS, Beijing. U-Th-Pb ratios and absolute abundances were determined relative to the standard zircon Plésovice (Slama et al. 2008), analyses of which were interspersed with those of unknown grains Qinghu (Supplementary Table S2) (Li et al. 2009), using operating and data processing procedures similar to those described by Li et al. (2009). Measured compositions were corrected for common Pb using non-radiogenic ^{204}Pb. Corrections are sufficiently small to be insensitive to the choice of common Pb composition, and an average of present-day crustal composition (Stacey and Kramers 1975) is used for the common Pb assuming that the common Pb is largely surface contamination introduced during sample preparation. Uncertainties on individual analyses in data tables are reported at a 1s level; mean ages for pooled U/Pb (and Pb/Pb) analyses are quoted with 95% confidence interval.

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