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Additional Analytical Methods

Detrital U-Pb Geochronology

Detrital zircon samples were collected from nine fine-, medium-, and coarse-grained sandstone beds (from sections 1LQ, 4LQ, 5LQ, 7LQ, and 9LQ; samples LQ-1, LQ-2, and LiuquTuff were collected separately) and 6 fine-grained intervals (from sections 1LQ, 8LQ, and 14LQ) within the Liuqu Conglomerate (see Figs. 2 and 4-9 for locations). These samples were processed according to standard crushing, sieving, water table, magnetic, and heavy liquid procedures. Zircon grains were then mounted in epoxy pucks, polished, and mapped with high resolution BSE imaging at the University of Arizona LaserChron Center. U-Pb ages of zircon grains were determined using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) (Gehrels et al., 2006, 2008; Gehrels and Pecha, 2014) at the University of Arizona LaserChron Center.

Most samples were ablated using a Photon Machines Analyte G2 excimer laser with a standard spot size of 30 microns. The ablated material was carried in helium gas into the plasma source of a Nu HR ICPMS equipped with a flight tube of sufficient width that U, Th, and Pb isotopes can be measured simultaneously. All measurements were made in static mode, using Faraday detectors with 3×10^{11} ohm resistors for ^{238}U , ^{232}Th , ^{208}Pb - ^{206}Pb , and discrete dynode ion counters for ^{204}Pb and ^{202}Hg . Ion yields were ~ 0.8 mv per ppm. Each analysis consisted of one 15-second integration on peaks with the laser off (for backgrounds), 15 one-second integrations with the laser firing, and a 30 second delay to purge the previous sample and prepare for the next analysis. The ablation pits were ~ 15 microns in depth. For each analysis, the errors in determining $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ resulted in a measurement error of ~ 1 -2% (at 2-sigma

level) in the $^{206}\text{Pb}/^{238}\text{U}$ age. The errors in measurement of $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ also resulted in ~1-2% (at 2-sigma level) uncertainty in age for grains that are >1.0 Ga, but are substantially larger for younger grains due to low intensity of the ^{207}Pb signal. For most analyses, the cross-over in precision of $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ ages occurs at ~1.0 Ga. ^{204}Hg interference with ^{204}Pb was accounted for by measurement of ^{202}Hg during laser ablation and subtraction of ^{204}Hg according to the natural $^{202}\text{Hg}/^{204}\text{Hg}$ of 4.35. This Hg is correction was not significant for most analyses because our Hg backgrounds were low (generally ~150 cps at mass 204).

Common Pb correction was accomplished by using the Hg-corrected ^{204}Pb and assuming an initial Pb composition from Stacey and Kramers (1975). Uncertainties of 1.5 for $^{206}\text{Pb}/^{204}\text{Pb}$ and 0.3 for $^{207}\text{Pb}/^{204}\text{Pb}$ were applied to these compositional values based on the variation in Pb isotopic composition in modern crystal rocks.

Inter-element fractionation of Pb/U is generally ~5%, whereas apparent fractionation of Pb isotopes is generally <0.2%. In-run analysis of fragments of a large zircon crystal (every sixth measurement) with known age of 563.5 ± 3.2 Ma (2-sigma error) was used to correct for this fractionation. The uncertainty resulting from the calibration correction was generally 1-2% (2-sigma) for both $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ ages. Concentrations of U and Th were calibrated relative to a Sri Lanka zircon, which contains ~518 ppm of U and 68 ppm Th.

Additional samples were analyzed via ablation of zircon with a Photon Analyte G2 excimer laser equipped with HelEx ablation cell using a spot diameter of 20 microns. The ablated material was carried in helium into the plasma source of an Element2 HR ICPMS, which sequences rapidly through U, Th, and Pb isotopes. Signal intensities were measured with an SEM that operates in pulse counting mode for signals less than 50K cps, in both pulse-counting

and analog mode for signals between 50K and 4M cps, and in analog mode above 4M cps. The calibration between pulse-counting and analog signals was determined line-by-line for signals between 50K and 4M cps, and was applied to 4M cps signals. Four intensities are determined and averaged for each isotope, with dwell times of 0.0052 sec for 202, 0.0075 sec for 204, 0.0202 sec for 206, 0.0284 sec for 207, 0.0026 sec for 208, 0.0026 sec for 232, and 0.0104 sec for 238.

With the laser set to an energy density of $\sim 5 \text{ J/cm}^2$, a repetition rate of 8 hz, and an ablation time of 10 seconds, ablation pits are ~ 12 microns deep. Sensitivity with these settings is approximately $\sim 5,000$ cps/ppm. Each analysis consists of 5 sec. on peaks with the laser off (for backgrounds), 10 sec. with the laser firing (for peak intensities), and a 20 second delay to purge the previous sample and save files.

MC-LA-ICPMS data were reduced using the program AgeCalc, while Single Collector data were reduced using the Python decoding routine E2AgeCalc. See www.laserchron.org for additional information. Uncertainties shown for individual grains in the supplemental data are at the 1-sigma level, and include only measurement errors, and systematic uncertainties for each sample are reported separately. Analyses that are >20% discordant or >5% reverse discordant are reported in the supplemental data but are not considered in interpretive aspects of this study.

Detrital Zircon Hf Analysis

Analyses were conducted with a Nu HR ICPMS connected to a Photon Machines Analyte G2 excimer laser using methods described by Gehrels and Pecha (2014). Instrument settings were established first by analysis of 10 ppb solutions of JMC475 and a Spex Hf solution, and then by analysis of 10 ppb solutions containing Spex Hf, Yb, and Lu. The mixtures ranged in concentration of Yb and Lu, with $^{176}(\text{Yb}+\text{Lu})$ up to 70% of the ^{176}Hf . When all solutions yielded

$^{176}\text{Hf}/^{177}\text{Hf}$ of ~ 0.28216 , instrument settings were optimized for laser ablation analyses and seven different standard zircons (Mud Tank, 91500, Temora, R33, FC52, Plesovice, and Sri Lanka) were analyzed. These standards were included with unknowns on the same epoxy mounts. When precision and accuracy were acceptable, unknowns were analyzed using exactly the same acquisition parameters.

Laser ablation analyses were conducted with a laser beam diameter of 40 microns, with the ablation pits located on top of the U-Pb analysis pits. CL images were used to ensure that the ablation pits did not overlap multiple age domains or inclusions. Each acquisition consisted of one 40-second integration on backgrounds (on peaks with no laser firing) followed by 60 one-second integrations with the laser firing. Using a typical laser fluence of $\sim 5 \text{ J/cm}^2$ and pulse rate of 7 hz, the ablation rate was ~ 0.8 microns per second. Each standard was analyzed once for every ~ 20 unknowns.

Isotope fractionation was accounted for using the method of Woodhead et al. (2004): βHf was determined from the measured $^{179}\text{Hf}/^{177}\text{Hf}$; βYb was determined from the measured $^{173}\text{Yb}/^{171}\text{Yb}$ (except for very low Yb signals); βLu was assumed to be the same as βYb ; and an exponential formula is used for fractionation correction. Yb and Lu interferences were corrected by measurement of $^{176}\text{Yb}/^{171}\text{Yb}$ and $^{176}\text{Lu}/^{175}\text{Lu}$ (respectively), as advocated by Woodhead et al. (2004). Critical isotope ratios were $^{179}\text{Hf}/^{177}\text{Hf} = 0.73250$ (Patchett & Tatsumoto, 1980); $^{173}\text{Yb}/^{171}\text{Yb} = 1.132338$ (Vervoort et al. 2004); $^{176}\text{Yb}/^{171}\text{Yb} = 0.901691$ (Vervoort et al., 2004; Amelin and Davis, 2005); $^{176}\text{Lu}/^{175}\text{Lu} = 0.02653$ (Patchett, 1983). All corrections were done line-by-line. For very low Yb signals, βHf is used for fractionation of Yb isotopes. The corrected $^{176}\text{Hf}/^{177}\text{Hf}$ values were filtered for outliers (2-sigma filter), and the average and standard error

were calculated from the resulting ~58 integrations. There is no capability to use only a portion of the acquired data.

All solutions, standards, and unknowns analyzed during a session were reduced together. The cutoff for using βHf versus βYb was determined by monitoring the average offset of the standards from their known values, and the cutoff was set at the minimum offset. For most data sets, this is achieved at ~6 mv of ^{171}Yb . For sessions in which the standards yield $^{176}\text{Hf}/^{177}\text{Hf}$ values that are shifted consistently from the known values, a correction factor was applied to the $^{176}\text{Hf}/^{177}\text{Hf}$ of all standards and unknowns. This correction factor, which is not necessary for most sessions, averages 1 epsilon unit.

The $^{176}\text{Hf}/^{177}\text{Hf}$ at time of crystallization was calculated from measurement of present-day $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{176}\text{Lu}/^{177}\text{Hf}$, using the decay constant of ^{176}Lu ($\lambda = 1.867\text{e}^{-11}$) from Scherer et al. (2001) and Söderlund et al. (2004). No capability is provided for calculating Hf Depleted Mantle model ages because the $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{176}\text{Lu}/^{177}\text{Hf}$ of the source material(s) from which the zircon crystallized is not known.

$^{40}\text{Ar}/^{39}\text{Ar}$ Analysis

Analyses were carried out at the Arizona Noble Gas Laboratory at the University of Arizona. Handpicked biotite grains were irradiated at the USGS TRIGA Reactor, Denver, Colorado along with flux monitors to calculate J-factors and K_2SO_4 and CaF_2 salts to calculate correction factors for interfering neutron reactions. Following a 2 to 3 week cooling period to allow for the decay of short-lived isotopes, samples were loaded into the arms of a glass storage tree above a double-vacuum, resistance-heated furnace and heated to 120° at the same time that the entire extraction line was baked for 48 hours at 220°C . Getters and furnace were

independently degassed near the end of the bake-out. Samples were then dropped into the furnace and argon was extracted from each sample using a computer controlled step-heating routine with 12 individual steps. The temperature of the furnace is estimated to be accurate to $\pm 20^{\circ}\text{C}$. Each heating step had a duration of 12 minutes followed by a cool down to 500°C prior to advancing the gas into two successive gettering stages for argon purification. The argon was then admitted into a VG 5400 mass spectrometer, where it was ionized and detected by a VG electron multiplier and digitized with a Keithley 617 Electrometer. Data collection and processing were accomplished using the computer program Mass Spec (Deino, 2001). The decay constants used were those recommended by Renne et al. (2010). Baseline values were subtracted and the isotopic measurements then were regressed to time zero using standard linear regression techniques. Additional corrections and associated uncertainties were applied to account for blanks, machine discrimination, atmospheric contribution, and interfering isotopes produced in the reactor from Ca, K and Cl present in the samples.

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