

## DESCRIPTION OF SUPPLEMENTARY MATERIAL

1. Analytical Methods (herein)
2. Supplementary.xls: The following spreadsheet data tables are included.
  - ZrnTE–SHRIMP: Trace elements in zircon
  - ZirconUPbSHRIMP: U/Th–Pb zircon SHRIMP data
  - MonaziteEMP: Electron microprobe monazite results
  - MonaziteSHRIMP: Monazite U/Th–Pb and trace element SHRIMP data
  - GrtTE: LA–ICPMS Trace elements in garnet
  - ApatiteEMP: Electron microprobe major elements in apatite
  - MnzProbeSettings: Electron microprobe settings for monazite analyses
3. EH09\_leucosome grt REE.pdf
4. Spot\_Locations.pdf: Zircon and monazite images showing SHRIMP and EMP analysis locations.

## ANALYTICAL METHODS

In situ techniques allow full textural information on a sample, thin section, and grain scale to be preserved. Knowledge of thin section scale context can indicate which accessory mineral grains occur as inclusions in porphyroblasts, which grains occur within what are interpreted as in situ leucosome segregations, and which grains are adjacent to large sinks/sources of trace elements such as high Y garnet. SIMS analysis of accessory mineral grains in thin section traditionally utilizes large portions of a thin section in order to present enough target material to be included in a single mount. This study involved microdrilling of accessory phase grains from thin sections to be combined in a composite mount for more efficient analysis of material from several thin sections or samples in a single SHRIMP session.

Zircon and monazite grains were located and grain context was imaged in thin section by petrographic microscope and on the Cameca SX100 electron microprobe at Rensselaer Polytechnic Institute. Extraction of individual thin section “plugs” including target grains was

performed using a Medenbach microdrill, following techniques similar to those of Paquette et al. (2004). Plugs were then remounted, imaged (cathodoluminescence [CL] and backscattered electron [BSE] for zircon, BSE and X-ray mapping for monazite), and monazites were analyzed by electron microprobe. One further remounting added polished zircon/monazite standards to produce a mount suitable for SHRIMP analysis. U/Th–Pb ages and trace element compositions were analyzed in a single session using the USGS / Stanford University SHRIMP–RG. Run conditions typically produced a round spot of ~10–15  $\mu\text{m}$  for zircon and ~15–20  $\mu\text{m}$  for monazite. Mass 204 correction for monazite followed Ireland et al. (1999). Data reduction utilized methods of Williams (1998) and Ireland and Williams (2003) using the Squid 2 and Isoplot programs of Ludwig (2003, 2009). Energy filtering was applied to discriminate against molecular interferences for monazite analyses, resulting in longer count times (~20 minutes per spot).  $^{206}\text{Pb}/^{238}\text{U}$  ages are corrected for common Pb using  $^{207}\text{Pb}$  (method described by Williams 1998) due to its greater abundance versus  $^{204}\text{Pb}$ . Matrix effects, or ionization efficiencies during SHRIMP monazite analysis were examined following the method of Fletcher et al. (2010). The Th content, considered representative of the bulk monazite matrix, versus age was compared for the standard and unknowns, suggesting indistinguishable matrix effects. SHRIMP ages determined for monazite were generally concordant in  $^{206}\text{Pb}/^{238}\text{U}$  vs.  $^{208}\text{Pb}/^{232}\text{Th}$  space. Th–Pb analyses are therefore reported here, using U–Pb isotopic data as monitor of common Pb and possible age domain mixtures. Zircon standard R33 (~419 Ma) and monazite 44069 (~425 Ma; J. Aleinikoff, personal communication; Aleinikoff et al. 2006) were used.

Individual grain extraction results in smaller numbers of grains per sample than “bulk sample crushing” mineral separation. Also, as a result of long counting times necessary for monazite energy filtering, fewer analyses were possible in a single analytical session (versus the U–Pb zircon routine). Therefore, coherent age groups yielding statistically robust mean ages (mean square of the weighted deviates [MSWD]  $\approx 1$ ) are not well constrained, and perhaps not realistic. As a result, age determinations reported here are presented as interpretations drawn from data reported in the Supplementary Material. Where reported, age groups were calculated as inverse-variance weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  ages for zircon and monazite (normally with a common Pb correction based on  $^{207}\text{Pb}$ ), with errors reported at 95% confidence. Individual spot analysis ages are reported with  $2\sigma$  errors.

Zircon trace element analyses were performed on the SHRIMP–RG in a session immediately preceding U–Pb analyses, including measurements of elemental peaks for  $^7\text{Li}$ ,  $^9\text{Be}$ ,  $^{11}\text{B}$ ,  $^{19}\text{F}$ ,  $^{23}\text{Na}$ ,  $^{27}\text{Al}$ ,  $^{30}\text{Si}$ ,  $^{31}\text{P}$ ,  $^{39}\text{K}$ ,  $^{40}\text{Ca}$ ,  $^{45}\text{Sc}$ ,  $^{48}\text{Ti}$ ,  $^{49}\text{Ti}$ ,  $^{56}\text{Fe}$ ,  $^{89}\text{Y}$ ,  $^{93}\text{Nb}$ ,  $^{96}\text{Zr}$ , and most REE's (La, Ce, Nd, Sm, Eu, Gd, and Ho). For Tb, Dy, Er, Tm, Yb, Lu, Hf, Th, and U, the heavier single-oxide peaks were measured because they produce significantly higher count rates. Spots analyzed covered generally the same grain location and utilized roughly the same primary beam current and effective spot size as for U–Pb analyses. Element concentrations were calculated by normalizing an average count rate to the average Zr count rate and correcting for isotopic abundance. Calibration was performed on Madagascar green zircon (MAD) following the methods of Mazdab and Wooden (2006). Uncertainties for REE Ce–Lu are on the order of 3–5% ( $1\sigma$ ) assuming a homogeneous standard.

A smaller set of monazite major and trace elements (Y, Sm, Eu, Gd, Dy, Er, Yb, Th, U) were analyzed simultaneously with U/Th–Pb analyses. Element concentrations were derived by normalizing the count rates to the average Nd count rate and correcting for isotopic abundance. Calibration was performed on standard NAM-2 yielding uncertainties on the order of 0.7–3% ( $1\sigma$ ) assuming a homogeneous standard.

Monazite electron microprobe X-ray mapping of grains for SHRIMP analysis utilized an accelerating voltage of 15keV, a current of 200 nA, and a dwell time of 30 ms/pixel. Pixel sizes for X-ray maps varied based on the size of the individual grains and zoning identified by BSE imaging, generally ranging between 0.3 and 1  $\mu\text{m}$ . Maps were processed using the freeware program ImageJ. Full monazite compositional analysis was performed by electron microprobe for samples EH09, EH10, EH31 and EH49. Analytical methods utilized the X-ray peaks indicated by Daniel and Pyle (2006), except for using Pb  $M\alpha$  as is appropriate for chemical dating on the Cameca SX-100 due to a different detector gas (see Spear et al. 2009). Analysis was performed at a current of 100 nA giving generally slightly lower detection limits than those reported in Daniel and Pyle (2006). These data were then compared with monazite SHRIMP trace element data in order to correlate age determinations with specific chemical domains fully characterized by electron microprobe analyses. Estimates of  $\text{OH}^-$  in apatite were calculated from major component analyses (Ca, P, F, Cl) performed with a 15 nA beam spread to 15  $\mu\text{m}$  using a 15 second dwell time, as per Pyle et al. (2002).

Garnet electron microprobe trace element X-ray mapping was performed with an accelerating voltage of 15keV, a variable pixel size depending on porphyroblast size, a dwell time of 100 milliseconds, and two different beam currents (1000 nA and 600 nA). The lower current proved sufficient and reduced the beam damage imposed on matrix phases and inclusions.

Table: Electron microprobe settings for monazite analyses.

Element	Spectrometer	Peak	Crystal	Peak position	Bkgd (-)	Bkgd (+)	Approx. DL (wt%)
P	1	K $\alpha$	TAP	23967	1071	1429	0.02
Si	1	K $\alpha$	TAP	27741	1071	1429	0.01
Y	1	L $\alpha$	TAP	25111	517	429	0.02
Pb	2	M $\alpha$	LPET	60377	3232	2239	0.01
Tb	5	L $\beta$	LLIF	44125	357	1429	0.10
Dy	5	L $\alpha$	LLIF	47397	1893	929	0.05
Er	5	L $\alpha$	LLIF	44310	2143	1286	0.05
Gd	5	L $\beta$	LLIF	45856	357	2143	0.15
Ce	5	L $\alpha$	LLIF	63616	1071	1429	0.12
Pr	5	L $\beta$	LLIF	56094	536	1786	0.15
Sm	5	L $\beta$	LLIF	49630	2036	2143	0.14
Nd	5	L $\beta$	LLIF	53803	1964	1821	0.19
La	5	L $\alpha$	LLIF	66213	1429	1429	0.12
S	3	K $\alpha$	LPET	61418	4286	1786	0.01
Ca	3	K $\alpha$	LPET	38388	893	893	0.01
Th	3	M $\alpha$	LPET	47288	1071	964	0.03
U	3	M $\beta$	LPET	42466	1729	536	0.03
Pb	4	M $\alpha$	LPET	60432	3232	2239	0.01

Trace elements in garnet from thin sections were measured by Laser Ablation – Inductively Coupled Plasma Mass Spectrometry (LA–ICMPS) at Rensselaer Polytechnic Institute. Garnet was ablated using a Photon Machines Analyte 193 nm ArF excimer laser with a 8 Hz repetition rate and Ar + He carrier gas. Spot size was approximately 30  $\mu$ m. A background analysis of 10–15 seconds preceded 40–60 second counting times for ablated material using time resolved peak hopping mode on the Varian Bruker 820-MS ICPMS. External calibration was performed on NIST 610 glass using the composition from Pearce et al. (1997).  $^{43}\text{Ca}$  was used as an internal standard with values determined by electron microprobe. Signal selection and data reduction were performed using the software GLITTER.

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