Supporting Information

Quantitative elemental mapping of granulite-facies monazite: textural insights and implications for petrochronology

Owen M. Weller\textsuperscript{1,2*}, Simon Jackson\textsuperscript{1}, William G.R. Miller\textsuperscript{2}, Marc R. St-Onge\textsuperscript{1}, Nicole Rayner\textsuperscript{1}

1 - Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8, Canada.
2 - Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, CB2 3EQ, UK.

*corresponding author: ow212@cam.ac.uk
APPENDIX S1

Sample locations

Meta Incognita Peninsula (MIP) has been the focus of two recent 1:100 000 mapping campaigns by the Geological Survey of Canada (GSC). The western portion was systematically mapped in 1995–1996, and targeted mapping of the eastern portion was completed in 2014 (Rayner, 2015; St-Onge et al., 2015). The samples analysed in this study were acquired during the 2014 mapping campaign. Sample 14SAB-A27A2 was collected from 62.2171°N, 67.2417°W. Sample 14SAB-O31A2 was collected from 63.1429°N, 69.3198°W.

Whole-rock analysis

Whole-rock major-element oxides (Table S1) for each sample were determined by lithium metaborate/tetraborate fusion inductively coupled plasma-mass spectrometry (ICP-MS) using a Perkin Elmer Sciex ELAN 6000 ICP-MS at Activation Laboratories Ltd., Canada. Two kilograms of each study sample was crushed in an agate mill for analysis (Fig. S2). FeO was determined by wet titration using a cold acid digestion of ammonium metavannate, and hydrofluoric acid in an open system. Ferrous ammonium sulfate was added after digestion, and potassium dichromate was the titrating agent. A corrected loss on ignition (LOI2) was determined accounting for ferrous-iron oxidation (Lechler & Desilets, 1987). C and S were determined by infrared.

Mineral composition analysis

Major element mineral compositional analyses (Tables S2–S3) were acquired on a JEOL JXA-8230 electron probe microanalyzer (EPMA) equipped with five wavelength-dispersive spectrometers (WDS) at the Department of Earth and Environmental Sciences, Ottawa University, using operating conditions of 20kV accelerating voltage and 20nA current. Standards were a mix of natural and synthetic minerals and metals, and the correction procedure of Pouchou & Pichoir (1991) was applied. Mineral cation totals were calculated using AX (Holland, 2009; accessed September 2017). Mineral abbreviations follow Whitney & Evans (2010).

SHRIMP analysis

In situ U–Pb isotopic analyses of monazite were carried out using a SHRIMP II at the Geological Survey of Canada (GSC). SHRIMP analysis employed the instrumental conditions and isobar filtering described in Stern & Berman (2000). The count rates at twelve masses including background (89Y, magnet settling peak mass 130, 203CePO2, 204Pb, 204.1bkgd,
$^{206}\text{Pb}$, $^{207}\text{Pb}$, $^{208}\text{Pb}$, $^{238}\text{U}$, $^{248}\text{ThO}$, $^{254}\text{UO}$, $^{270}\text{UO}_2$) were sequentially measured over 6 scans with a single electron multiplier and a pulse counting system with a dead-time of 20 ns. Data was reduced using SQUID 2.50.11.10.15, rev. 15 Oct 2011. All other analytical details including reference materials are reported as footnotes in Tables S5 & S6.

LA-ICP-MS mapping

Quantitative elemental mapping of seven monazite grains from sample 14SAB-A27A2 and two monazite grains from sample 14SAB-O31A2 was performed by laser ablation-inductively coupled plasma-mass spectrometer (LA-ICP-MS) analysis at the GSC. The monazite grains were retained in the polished 25 mm diameter epoxy grain mounts used for SHRIMP analysis, with the gold coating removed and the samples cleaned in an ultrasonic bath prior to trace element analysis.

The laser ablation sampler uses a focussed, pulsed UV laser beam to ablate a small amount of sample contained in a sample cell. The ablated material is carried in a continuous flow of helium to an ICP-MS, which vaporises and ionises the transported particulates in an inductively coupled argon plasma, separates the ions based on their mass/charge ratio and measures the signal intensity for selected isotopes. In this work, an Analyte193 laser ablation sampler (Photon Machines Inc.), based on an ArF excimer laser ($\lambda = 193$ nm), was coupled to an Agilent 7700x quadrupole ICP-MS. The Analyte 193 was equipped with a HelEx 2-volume cell that provides fast washout (>2 orders of magnitude per second). For this work, no smoothing device was used. The ICP-MS was equipped with a second interface rotary pump, which approximately doubles instrument sensitivity.

The SHRIMP mount, an elemental calibration standard (NIST SRM 610) and a U–Pb calibration standard (monazite 2908) were loaded into the sample cell for analysis. The laser ablation and ICP-MS operating conditions used are presented in Table S7. Mapping was achieved by blanketing selected grains with contiguous, parallel line scan ablations while acquiring data on 24 isotopes using a fast time-resolved data acquisition protocol, which provided signal intensity data in counts per second (cps) for each mass sweep of the mass spectrometer (166.7 ms). Prior to the data acquisition ablation pass, each line was first rapidly pre-ablated (3 laser pulses per position) to remove surface contamination. The ICP-MS data for each line were saved as a separate analysis file, with each analysis consisting of measurement of the laser-off background (‘gas blank’) for 20 s, followed by the ablation signal for up to 180 s. All mapping was performed using nominal ablation spot diameters of 4 or 5 $\mu$m. Calibration standards NIST SRM 610 and monazite 2908 were analysed twice and four times, respectively, before and after each monazite sample to calibrate the mass response of the ICP-MS and allow correction for instrumental mass-dependent sensitivity drift. The same ablation conditions were used for samples and standards except a 6 $\mu$m spot size was used for all analyses of NIST 610 to ensure sufficient signal intensities for accurate calibration.
The data were processed with in-house software (Convert; LAMTrace, Jackson, 2008; and PixeLAtE) in three stages:

1. The time-resolved signal intensity data for each line were integrated in multiples (12) of mass sweeps to convert the signal intensity data into 2 s readings, each of which would ultimately form 1 pixel in an element content map. Signal intensity data for $^{206}\text{Pb}$, $^{207}\text{Pb}$ and $^{208}\text{Pb}$ were summed (Pb(tot)).

2. Background-corrected signal intensity data were standardised against NIST 610 (elemental contents) and monazite 2908 (U–Pb ages). ‘GeoReM preferred values’ were used for the elemental contents of NIST 610 (http://georem.mpch-mainz.gwdg.de/). Lead concentrations were calculated using Pb(tot) to account for the different isotopic abundances of the Pb isotopes between sample and standard. Because of the potential for significant within-grain variation of all the major elements in the monazites, conventional internal standardisation to correct for ablation yield differences between sample and standard (Longerich et al., 1996) was not used. Instead, ablation yield correction was achieved via normalisation to 100% total elemental abundance (Halicz & Gunther, 2004). Elemental concentrations were first converted to wt% oxides on a pixel-by-pixel basis. As P could not be calibrated using NIST 610 as a standard, $\text{P}_2\text{O}_5$ was calculated based on the molar abundances of Ca, Y, REE, Th and U in each pixel. The oxide concentrations of all elements were then summed and normalised to 100% on a pixel-by-pixel basis. Pixels for which the Ce signal intensity was $< 15\%$ of the signal for pure monazite were flagged. Mean detection limits for the pixels in each map were calculated. Measured concentrations are generally well in excess of the detection limits.

3. Element content and age data for each pixel were deconvoluted, assembled and converted into 2-D false-colour maps by assigning colours based a scaling function that linearly scaled the central 90% of the concentration values, and assigned the lowest 5% and highest 5% of the values to the lowest (black) and highest (dark red) colour bins, respectively. Pixels flagged as having a recorded Ce signal of $< 15\%$ of the signal for pure monazite were assigned a white colour.

While U–Pb and $^{207}\text{Pb}/^{206}\text{Pb}$ age maps were generated, because of the small spot size (4 or 5 $\mu\text{m}$), short integration times per pixel (2 s) and large number of isotopes determined (24), the precision of the technique was not sufficiently good to allow different age domains within individual monazite grains to be distinguished. The LA-ICP-MS age maps are not therefore discussed in this paper.
SUPPLEMENTARY FIGURES

Figure S1 | Whole rock ICP-MS samples. (a) 14SAB-O31A2. (b) 14SAB-A27A2. Pen is 12.5 cm long for scale.

Figure S2 | Melt reintegration example for sample 14SAB-A27A2. $T$–$X$ pseudosection ($P = 10$ kbar). $X = 0$ is the A27A2 whole-rock bulk composition; $X = 1$ is the A27A2 bulk composition with 25 mol.% melt, with the melt composition used of the whole-rock 10 kbar solidus. The red circle highlights where sufficient melt has been integrated into the bulk composition such that the solidus (bold black line) becomes water saturated (i.e. intercepts H$_2$O-in (light blue line)). This bulk composition is used to model the prograde evolution of the sample (Fig. 6b).
Figure S3 | 14SAB-O31A2 phase vol.% maps. Calculated using the pixel mapping function of Theriak-Domino (De Capitani & Petrakakis, 2010).
Figure S4 | 14SAB-A27A2 phase vol.% maps Calculated using the pixel mapping function of Theriak-Domino (De Capitani & Petrakakis, 2010).
| Analysis (14SAB-O31A2-) | BSE | Th (ppm) | Th WDS map | Y (ppm) | Y WDS map |
|--------------------------|-----|----------|------------|---------|-----------|
| 1-22.1                   |     | 26088    |            | 803     |           |
| 2-62.1                   |     | 41772    |            | 449     |           |
| 2-60.1                   |     | 39532    |            | 879     |           |
| 1-19.1                   |     | 29625    |            | 542     |           |
| 2-12.1                   |     | 24375    |            | 959     |           |
| 1-17.1                   |     | 38043    |            | 2110    |           |
| 2-48.1                   |     | 50520    |            | 402     |           |
| 1-130.2                  |     | 39590    |            | 613     |           |
| 2-13.1                   |     | 42685    |            | 2495    |           |
| 2-107.1                  |     | 18473    |            | 843     |           |
| 2-104.1                  |     | 38639    |            | 869     |           |
| 1-105.2                  |     | 37513    |            | 589     |           |
| 1-21.1                   |     | 57870    |            | 6324    |           |

Figure S5 | 14SAB-O31A2 monazite BSE, Th and Y images. Grains are listed in age order as per Table S5. White circles show SHRIMP spot location and are 10 µm for scale. Blue text denotes grains located in the leucosome, green text the melanosome and red text in garnet.
| Analysis (14SAB-O31A2-) | BSE | Th (ppm) | Th WDS map | Y (ppm) | Y WDS map |
|--------------------------|-----|----------|------------|---------|-----------|
| 2-61.1                   | ![BSE image] | 31026     | ![Th WDS map] | 14386   | ![Y WDS map] |
| 1-143.1                  | ![BSE image] | 38968     | ![Th WDS map] | 4089    | ![Y WDS map] |
| 2-66.1                   | ![BSE image] | 34274     | ![Th WDS map] | 1213    | ![Y WDS map] |
| 1-105.1                  | ![BSE image] | 14918     | ![Th WDS map] | 11411   | ![Y WDS map] |
| 2-59.1                   | ![BSE image] | 32677     | ![Th WDS map] | 6202    | ![Y WDS map] |
| 2-51.1                   | ![BSE image] | 42927     | ![Th WDS map] | 11183   | ![Y WDS map] |
| 2-49.1                   | ![BSE image] | 37506     | ![Th WDS map] | 3397    | ![Y WDS map] |
| 1-130.1                  | ![BSE image] | 12516     | ![Th WDS map] | 12038   | ![Y WDS map] |

Fig. S5 cont.
Figure S6 | 14SAB-A27A2 monazite BSE, Th and Y images. Grains are listed in age order as per Table S6. White circles show SHRIMP spot location and are 10 µm for scale. Blue text denotes grains located in the leucosome, green text the melanosome and red text in garnet.
### Analysis

| Analysis (14SAB-A27A2- | BSE | Th (ppm) | Th WDS map | Y (ppm) | Y WDS map |
|--------------------------|-----|----------|-------------|---------|-----------|
| 1-27.2                   | ![BSE Image] | 56240    | ![Th Image] | 15238   | ![Y Image] |
| 1-120.1                  | ![BSE Image] | 63985    | ![Th Image] | 17014   | ![Y Image] |
| 1-25.1                   | ![BSE Image] | 62689    | ![Th Image] | 17308   | ![Y Image] |
| 1-100.2                  | ![BSE Image] | 34732    | ![Th Image] | 11652   | ![Y Image] |
| 1-27.1                   | ![BSE Image] | 71297    | ![Th Image] | 18355   | ![Y Image] |
| 2-48.1                   | ![BSE Image] | 44552    | ![Th Image] | 14044   | ![Y Image] |
| 1-100.1                  | ![BSE Image] | 41479    | ![Th Image] | 13604   | ![Y Image] |
| 1-114.1                  | ![BSE Image] | 59180    | ![Th Image] | 15842   | ![Y Image] |
| 1-116.1                  | ![BSE Image] | 43122    | ![Th Image] | 19537   | ![Y Image] |
| 1-111.1                  | ![BSE Image] | 68291    | ![Th Image] | 28069   | ![Y Image] |
| 1-51.1                   | ![BSE Image] | 56405    | ![Th Image] | 14545   | ![Y Image] |
| 2-132.1                  | ![BSE Image] | 50653    | ![Th Image] | 11358   | ![Y Image] |
| 1-54.1                   | ![BSE Image] | 63016    | ![Th Image] | 19392   | ![Y Image] |

Fig. S6 cont.
| Analysis (14SAB-A27A2-) | BSE | Th (ppm) | Th WDS map | Y (ppm) | Y WDS map |
|-----------------|-----|----------|------------|---------|-----------|
| 1-52.1          | ![BSE Image](image1) | 57048    | ![Th WDS Image](image2) | 14873   | ![Y WDS Image](image3) |
| 2-47.1          | ![BSE Image](image4) | 45883    | ![Th WDS Image](image5) | 10722   | ![Y WDS Image](image6) |
| 2-50.1          | ![BSE Image](image7) | 45626    | ![Th WDS Image](image8) | 15916   | ![Y WDS Image](image9) |
| 1-25.2          | ![BSE Image](image10) | 47964    | ![Th WDS Image](image11) | 20941   | ![Y WDS Image](image12) |
| 1-39.1          | ![BSE Image](image13) | 34111    | ![Th WDS Image](image14) | 11527   | ![Y WDS Image](image15) |
| 2-132.2         | ![BSE Image](image16) | 41989    | ![Th WDS Image](image17) | 23222   | ![Y WDS Image](image18) |
| 2.49.2          | ![BSE Image](image19) | 32818    | ![Th WDS Image](image20) | 13096   | ![Y WDS Image](image21) |

Fig. S6 cont.
Figure S7 | Example set of LA-ICP-MS maps for one grain (14SAB-A27A2-2-132). Pixel size = 5 µm. The maps linearly scale the central 90% of the concentration values, and put the extreme low and high values in the lowest (black) and highest (dark red) colour bins, respectively. Oxide scales are in wt.%, isotope scales are in ppm.
Figure S8 | Comparison of (a) Y and (b) Yb/Gd vs Eu/Eu* for grain 14SAB-A27A2-2-132. Similar trends are observed, emphasising that Y content is an effective proxy for HREE fractionation.
Figure S9 | Monazite grain 14SAB-A27A2-1-116 analysis. (a) BSE image showing monazite location in the leucosome. (b) BSE image of grain showing SHRIMP pits and ages. (c,d) Qualitative EPMA maps of (c) Th and (d) Y; brighter colours = higher concentration. Y map is overlain by interpreted growth zones; see text for details. (e) Chondrite-normalised REE diagram for data for every pixel in the LA-ICP-MS element maps, colour coded by Th/U. (f) Eu/Eu$^*$–Y plot, colour-coded by Th/U, with corresponding data density map (g). Numbers refer to growth zones, circles to end-member compositions and dotted lines to mixing; see text for details. KDE = Kernel density estimation. (h–j) LA-ICP-MS maps of (h) Y$_2$O$_3$ (wt.%), (i) Eu/Eu$^*$ and (j) Th/U. Pixel size = 4 µm. The maps linearly scale the central 90% of the concentration values, and put the extreme low and high values in the lowest (black) and highest (dark red) colour bins, respectively.
Figure S10 | Monazite grain 14SAB-A27A2-1-25 analysis. (a) BSE image showing monazite location in the melanosome. (b) BSE image of grain showing SHRIMP pits and ages. (c,d) Qualitative EPMA maps of (c) Th and (d) Y; brighter colours = higher concentration. Y map is overlain by interpreted growth zones; see text for details. (e) Chondrite-normalised REE diagram for data for every pixel in the LA-ICP-MS element maps, colour coded by Th/U. (f) Eu/Eu*–Y plot colour-coded by Th/U, with corresponding data density map (g). Numbers refer to growth zones, circles to end-member compositions and dotted lines to mixing; see text for details. KDE = Kernel density estimation. (h–j) LA-ICP-MS maps of (h) Y₂O₃ (wt.%), (i) Eu/Eu* and (j) Th/U. Pixel size = 4 µm. The maps linearly scale the central 90% of the concentration values, and put the extreme low and high values in the lowest (black) and highest (dark red) colour bins, respectively.
Figure S11 | Monazite grain 14SAB-A27A2-1-27 analysis. (a) BSE image showing monazite location in the melanosome. (b) BSE image of grain showing SHRIMP pits and ages. (c,d) Qualitative EPMA maps of (c) Th and (d) Y; brighter colours = higher concentration. Y map is overlain by interpreted growth zones; see text for details. (e) Chondrite-normalised REE diagram for data for every pixel in the LA-ICP-MS element maps, colour coded by Th/U. (f) Eu/Eu*–Y plot colour-coded by Th/U, with corresponding data density map (g). Numbers refer to growth zones, circles to end-member compositions and dotted lines to mixing; see text for details. KDE = Kernel density estimation. (h–j) LA-ICP-MS maps of (h) Y₂O₃ (wt.%), (i) Eu/Eu* and (j) Th/U. Pixel size = 4 µm. The maps linearly scale the central 90% of the concentration values, and put the extreme low and high values in the lowest (black) and highest (dark red) colour bins, respectively.
Figure S12 | Monazite grain 14SAB-O31A2-1-105 analysis. (a) BSE image showing monazite location in garnet in the melanoosome. (b) BSE image of grain showing SHRIMP pits and ages. (c,d) Qualitative EPMA maps of (c) Th and (d) Y; brighter colours = higher concentration. Y map is overlain by interpreted growth zones; see text for details. (e) Chondrite-normalised REE diagram for data for every pixel in the LA-ICP-MS element maps, colour coded by Th/U. (f) Eu/Eu*-Y plot colour-coded by Th/U, with corresponding data density map (g). Numbers refer to growth zones, circles to end-member compositions and dotted lines to mixing; see text for details. KDE = Kernel density estimation. (h–j) LA-ICP-MS maps of (h) Y₂O₃ (wt.%), (i) Eu/Eu* and (j) Th/U. Pixel size = 4 μm. The maps linearly scale the central 90% of the concentration values, and put the extreme low and high values in the lowest (black) and highest (dark red) colour bins, respectively.
SUPPLEMENTARY TABLES

Table S1 | Whole-rock data (wt%). FeO (hence XFe\(^{3+}\)) determined by wet titration. C and S determined by infrared. All other analyses determined by fusion ICP-MS. Detection limits are implied by the displayed precision. LOI_2 = LOI + 0.111*FeO (Lechler & Desilets, 1987). H\(_2\)O = LOI_2 - (C + S).

| Sample     | SiO\(_2\) | TiO\(_2\) | Al\(_2\)O\(_3\) | Fe\(_2\)O\(_3\) | FeO | MnO | MgO | CaO | Na\(_2\)O | K\(_2\)O | P\(_2\)O\(_5\) | LOI_2 | Total | C   | S   | H\(_2\)O | XFe\(^{3+}\) |
|------------|-----------|-----------|-----------------|-----------------|-----|-----|-----|-----|----------|--------|-----------|-------|-------|-----|-----|----------|-----------|
| 14SAB-O31A2| 74.31     | 0.721     | 12.25           | 2.09            | 3.3 | 0.107 | 2.12 | 0.75 | 0.80     | 2.11   | 0.04      | 0.96   | 0.06  | 0.09 | 0.81     | 0.36      |
| 14SAB-A27A2| 60.47     | 1.081     | 19.39           | 5.40            | 3.9 | 0.105 | 1.78 | 0.37 | 1.29     | 4.44   | 0.05      | 1.08   | 0.11  | 0.00 | 0.97     | 0.55      |
Table S2 | Representative sample 14SAB-O31A2 EMPA-WDS phase data.

Wt% analyses are raw microprobe data, whereas cation totals were calculated using AX (Holland, 2009). Data are representative single-spot analyses; multiple petrographic location data are given for zoned minerals. $X_{Mg} = Mg/(Mg + Fe^{2+})$; $X_{Fe^{3+}} = Fe^{3+}/(Fe^{2+} + Fe^{3+})$; Sps = Mn/(Fe$^{2+}$ + Mg + Ca + Mn); Prp = Mg/(Fe$^{2+}$ + Mg + Ca + Mn); Grs = Ca/(Fe$^{2+}$ + Mg + Ca + Mn); Alm = Fe$^{2+}$/(Fe$^{2+}$ + Mg + Ca + Mn); $X_{An} = Ca/(Na + Ca)$.

| Mineral Location | Bt melanosome | Crd melanosome | Grt core | Grt rim | Ilm melanosome | Kfs leucosome | Pl leucosome |
|------------------|--------------|----------------|----------|---------|----------------|--------------|-------------|
| SiO₂             | 36.56        | 48.55          | 38.41    | 37.19   | 0.00           | 64.14        | 59.19       |
| TiO₂             | 4.56         | 0.00           | 0.02     | 0.03    | 52.93          | 0.00         | 0.00        |
| Al₂O₃            | 16.15        | 33.45          | 21.62    | 21.25   | 0.00           | 18.83        | 25.71       |
| Cr₂O₃            | 0.06         | 0.00           | 0.02     | 0.04    | 0.09           | 0.00         | 0.00        |
| FeO              | 13.25        | 5.84           | 29.30    | 33.09   | 45.95          | 0.04         | 0.00        |
| MnO              | 0.03         | 0.03           | 0.86     | 1.21    | 0.23           | 0.00         | 0.00        |
| MgO              | 14.51        | 10.31          | 8.65     | 6.00    | 0.81           | 0.00         | 0.00        |
| CaO              | 9.81         | 0.00           | 0.00     | 0.00    | 0.00           | 15.00        | 0.17        |
| Na₂O             | 0.11         | 0.04           | 0.01     | 0.03    | 0.00           | 1.16         | 7.28        |
| K₂O              | 0.00         | 0.03           | 1.13     | 1.14    | 0.02           | 0.03         | 7.29        |
| Total            | 95.03        | 98.25          | 100.02   | 99.98   | 100.04         | 99.20        | 99.64       |
| Si               | 2.72         | 4.94           | 2.98     | 2.94    | 0.00           | 2.98         | 2.65        |
| Ti               | 0.26         | 0.00           | 0.00     | 0.00    | 1.00           | 0.00         | 0.00        |
| Al               | 1.42         | 4.01           | 1.97     | 1.98    | 0.00           | 1.03         | 1.36        |
| Cr               | 0.00         | 0.00           | 0.00     | 0.00    | 0.00           | 0.00         | 0.00        |
| Fe³⁺             | 0.00         | 0.10           | 0.07     | 0.14    | 0.00           | 0.00         | 0.00        |
| Fe²⁺             | 0.83         | 0.40           | 1.83     | 2.05    | 0.96           | 0.00         | 0.00        |
| Mn               | 0.00         | 0.00           | 0.06     | 0.08    | 0.01           | 0.00         | 0.00        |
| Mg               | 1.61         | 1.56           | 1.00     | 0.71    | 0.03           | 0.00         | 0.00        |
| Ca               | 0.00         | 0.00           | 0.09     | 0.10    | 0.00           | 0.00         | 0.35        |
| Na               | 0.02         | 0.01           | 0.00     | 0.01    | 0.00           | 0.10         | 0.63        |
| K                | 0.93         | 0.00           | 0.00     | 0.00    | 0.00           | 0.89         | 0.01        |
| Sum              | 7.79         | 11.02          | 8.00     | 8.00    | 2.00           | 5.00         | 5.00        |
| Oxygens          | 11           | 18             | 12       | 12      | 3              | 8            | 8           |
| $X_{Mg}$         | 0.66         | 0.80           | 0.35     | 0.26    | 0.03           | -            | -           |
| $X_{Fe^{3+}}$    | 0.00         | 0.20           | 0.04     | 0.06    | 0.00           | -            | -           |
| Sps              | -            | -              | 0.02     | 0.03    | -              | -            | -           |
| Prp              | -            | -              | 0.34     | 0.24    | -              | -            | -           |
| Grs              | -            | -              | 0.03     | 0.03    | -              | -            | -           |
| Alm              | -            | -              | 0.61     | 0.70    | -              | -            | -           |
| $X_{An}$         | -            | -              | -        | -       | 0.01           | 0.36         | -           |
Table S3 | Representative sample 14SAB-A27A2 EMPA-WDS phase data.
Wt% analyses are raw microprobe data, whereas cation totals were calculated using AX (Holland, 2009). Data are representative single-spot analyses; multiple petrographic location data are given for zoned minerals. \(X_{\text{Mg}} = \text{Mg}/(\text{Mg} + \text{Fe}^{2+})\); \(X_{\text{Fe}^{3+}} = \text{Fe}^{3+}/(\text{Fe}^{2+} + \text{Fe}^{3+})\); Sps = Mn/(Fe\(^{2+}\) + Mg + Ca + Mn); Prp = Mg/(Fe\(^{2+}\) + Mg + Ca + Mn); Grs = Ca/(Fe\(^{2+}\) + Mg + Ca + Mn); Alm = Fe\(^{2+}\)/(Fe\(^{2+}\) + Mg + Ca + Mn); \(X_{\text{An}} = \text{Ca}/(\text{Na} + \text{Ca})\).

| Mineral Location | Bt melanosome | Crd leucosome | Grt core | Grt rim | Ilm melanosome | Kfs leucosome | Mag melanosome | Spl melanosome |
|------------------|---------------|--------------|----------|---------|---------------|---------------|---------------|---------------|
| SiO\(_2\)        | 35.21         | 48.33        | 38.01    | 37.32   | 0.00          | 64.47         | 0.00          | 0.00          |
| TiO\(_2\)        | 3.07          | 0.01         | 0.00     | 0.01    | 51.32         | 0.00          | 0.05          | 0.01          |
| Al\(_2\)O\(_3\)  | 17.87         | 33.34        | 21.66    | 21.25   | 0.00          | 18.63         | 0.22          | 57.80         |
| Cr\(_2\)O\(_3\)  | 0.01          | 0.00         | 0.00     | 0.00    | 0.01          | 0.00          | 0.15          | 0.16          |
| FeO              | 15.92         | 5.47         | 29.95    | 32.59   | 47.20         | 0.01          | 93.11         | 33.20         |
| MnO              | 0.08          | 0.20         | 2.36     | 2.31    | 0.50          | 0.00          | 0.03          | 0.16          |
| MgO              | 12.48         | 10.18        | 7.22     | 5.51    | 0.66          | 0.00          | 0.02          | 7.53          |
| CaO              | 0.00          | 0.01         | 0.68     | 0.73    | 0.01          | 0.99          | 0.00          | 0.00          |
| Na\(_2\)O        | 0.07          | 0.04         | 0.00     | 0.00    | 0.00          | 1.33          | 0.00          | 0.00          |
| K\(_2\)O         | 9.61          | 0.00         | 0.00     | 0.00    | 0.00          | 14.79         | 0.00          | 0.00          |
| Total            | 94.33         | 97.57        | 99.88    | 99.72   | 99.71         | 99.31         | 93.57         | 98.85         |

| Oxygens          | 11            | 18           | 12       | 12      | 3             | 8             | 4             | 4             |

\(X_{\text{Mg}}\)  0.58  0.81  0.30  0.24  0.03  -  0.00  0.31  
\(X_{\text{Fe}^{3+}}\) 0.00  0.20  0.02  0.03  0.06  -  0.66  0.12  
Sps  -  -  0.05  0.05  -  -  -  -  
Prp  -  -  0.28  0.22  -  -  -  -  
Grs  -  -  0.02  0.02  -  -  -  -  
Alm  -  -  0.65  0.71  -  -  -  -  
\(X_{\text{An}}\)  -  -  -  -  -  0.03  -  -  

Si  2.67  4.94  2.98  2.97  0.00  2.99  0.00  0.00  
Ti  0.18  0.00  0.00  0.00  0.97  0.00  0.00  0.00  
Al  1.60  4.02  2.00  1.99  0.00  1.02  0.01  1.90  
Cr  0.00  0.00  0.00  0.00  0.00  0.00  0.01  0.00  
Fe\(^{3+}\) 0.00  0.09  0.04  0.07  0.06  0.00  1.98  0.09  
Fe\(^{2+}\) 1.01  0.37  1.92  2.10  0.94  0.00  1.00  0.68  
Mn  0.01  0.02  0.16  0.16  0.01  0.00  0.00  0.00  
Mg  1.41  1.55  0.84  0.65  0.03  0.00  0.00  0.31  
Ca  0.00  0.00  0.06  0.06  0.00  0.00  0.00  0.00  
Na  0.01  0.01  0.00  0.00  0.00  0.12  0.00  0.00  
K  0.93  0.00  0.00  0.00  0.00  0.87  0.00  0.00  
Sum 7.82  11.01  8.00  8.00  2.00  5.00  3.00  3.00  

| Sum | 11 | 18 | 12 | 12 | 3 | 8 | 4 | 4 |
|-----|----|----|----|----|---|---|---|---|
| Si  | 2.67 | 4.94 | 2.98 | 2.97 | 0.00 | 2.99 | 0.00 | 0.00 |
| Ti  | 0.18 | 0.00 | 0.00 | 0.00 | 0.97 | 0.00 | 0.00 | 0.00 |
| Al  | 1.60 | 4.02 | 2.00 | 1.99 | 0.00 | 1.02 | 0.01 | 1.90 |
| Cr  | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| Fe\(^{3+}\) | 0.00 | 0.09 | 0.04 | 0.07 | 0.06 | 0.00 | 1.98 | 0.09 |
| Fe\(^{2+}\) | 1.01 | 0.37 | 1.92 | 2.10 | 0.94 | 0.00 | 1.00 | 0.68 |
| Mn  | 0.01 | 0.02 | 0.16 | 0.16 | 0.01 | 0.00 | 0.00 | 0.00 |
| Mg  | 1.41 | 1.55 | 0.84 | 0.65 | 0.03 | 0.00 | 0.00 | 0.31 |
| Ca  | 0.00 | 0.00 | 0.06 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na  | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.12 | 0.00 | 0.00 |
| K   | 0.93 | 0.00 | 0.00 | 0.00 | 0.00 | 0.87 | 0.00 | 0.00 |
| Sum | 7.82 | 11.01 | 8.00 | 8.00 | 2.00 | 5.00 | 3.00 | 3.00 |
Table S4 | THERMOCALC inputs (mol.%). FeO' = total FeO. THERMOCALC treats $\text{Fe}_2\text{O}_3 = 2\text{FeO} + \text{O}$. Therefore, $X\text{Fe}^{3+} = 2\text{O}/\text{FeO}'$.

| Fig. | Sample (14SAB-) | H$_2$O | SiO$_2$ | Al$_2$O$_3$ | CaO | MgO | FeO' | K$_2$O | Na$_2$O | TiO$_2$ | MnO | O | $X\text{Fe}^{3+}$ | XMg |
|------|-----------------|--------|--------|-------------|-----|-----|------|--------|--------|--------|-----|---|-----------------|-----|
| 3a-c | O31A2           | 2.81   | 77.37  | 7.52        | 0.81| 3.29| 4.51 | 1.40   | 0.81   | 0.56   | 0.09| 0.82| 0.36            | 0.53|
| 3b,c | O31A2 (X=0)     | 0.10   | 79.53  | 7.73        | 0.83| 3.38| 4.64 | 1.44   | 0.83   | 0.58   | 0.10| 0.84| 0.36            | 0.53|
| 3d   | A27A2           | 3.52   | 65.37  | 12.36       | 0.39| 2.87| 7.92 | 3.06   | 1.35   | 0.88   | 0.10| 2.19| 0.55            | 0.45|
| -    | O31A2 (10 kbar melt) | 36.08 | 50.80  | 6.63        | 0.50| 0.10| 0.14 | 1.09   | 4.65   | 0.00   | 0.00| 0.00| 0.00            | 0.40|
| S2   | A27A2 (10 kbar melt) | 27.79 | 57.46  | 7.49        | 0.38| 0.11| 0.22 | 2.34   | 4.22   | 0.00   | 0.00| 0.00| 0.00            | 0.34|
| 4a   | O31A2 melt reintegrated | 3.03 | 77.19  | 7.51        | 0.81| 3.27| 4.48 | 1.40   | 0.84   | 0.56   | 0.09| 0.81| 0.36            | 0.53|
| 4b   | A27A2 melt reintegrated | 7.44 | 64.09  | 11.57       | 0.39| 2.42| 6.68 | 2.94   | 1.81   | 0.74   | 0.08| 1.84| 0.55            | 0.45|
Table S5 | Sample 14SAB-O31A2 U–Pb monazite data (GSC lab number z11861).

| Analysis | Petrographic position | U (ppm) | Th (ppm) | Y (ppm) | 232Th/238U | 206Pb*/204Pb corr. ± (206Pb*/204Pb) | 207Pb*/206Pb corr. ± (207Pb*/206Pb) | 208Pb*/206Pb corr. ± (208Pb*/206Pb) | Error Corr. |
|----------|-----------------------|---------|----------|---------|-----------|-----------------------------------|-----------------------------------|-----------------------------------|-------------|
| O31A2-1-022.1 Leucosome | 1275 | 26988 | 803 | 21.1 | 343 | 4.6E-5 | 0.08 | 6.5 | 0.64 | 4.77 | 1.8 | 0.3136 | 1.7 | 0.94 |
| O31A2-2-062.1 Melanosome | 920 | 41772 | 449 | 46.9 | 263 | 1.1E-4 | 0.20 | 13.6 | 0.82 | 5.06 | 2.3 | 0.3311 | 1.8 | 0.80 |
| O31A2-2-086.1 Melanosome | 1504 | 39293 | 879 | 27.2 | 424 | 7.8E-5 | 0.14 | 8.1 | 0.62 | 5.09 | 1.6 | 0.3280 | 1.5 | 0.95 |
| O31A2-1-019.1 Leucosome | 1186 | 29625 | 542 | 25.8 | 330 | 9.5E-5 | 0.17 | 7.8 | 0.30 | 4.96 | 1.5 | 0.3245 | 1.4 | 0.95 |
| O31A2-2-012.1 Leucosome | 1297 | 24375 | 959 | 19.4 | 367 | 7.8E-5 | 0.08 | 5.9 | 0.38 | 5.04 | 1.3 | 0.3280 | 1.1 | 0.95 |
| O31A2-1-017.1 Melanosome | 1477 | 38043 | 2110 | 26.6 | 428 | 1.2E-4 | 0.20 | 7.9 | 0.35 | 5.17 | 1.4 | 0.3373 | 1.3 | 0.93 |
| O31A2-2-048.1 Melanosome | 976 | 50520 | 402 | 53.5 | 275 | 1.0E-4 | 0.19 | 15.8 | 0.55 | 5.04 | 1.3 | 0.3280 | 1.1 | 0.89 |
| O31A2-2-013.1 Leucosome | 1655 | 39590 | 613 | 24.7 | 479 | 1.2E-4 | 0.21 | 7.3 | 0.74 | 5.19 | 1.3 | 0.3368 | 1.3 | 0.93 |
| O31A2-2-013.2 Garnet | 2195 | 42685 | 2495 | 20.1 | 653 | 9.4E-5 | 0.17 | 6.1 | 0.84 | 5.34 | 1.4 | 0.3464 | 1.3 | 0.95 |
| O31A2-1-021.1 Leucosome | 1279 | 18473 | 843 | 14.9 | 367 | 9.5E-5 | 0.17 | 4.5 | 0.43 | 5.16 | 1.4 | 0.3268 | 1.2 | 0.94 |
| O31A2-2-107.1 Melanosome | 1129 | 38639 | 869 | 35.4 | 334 | 1.1E-4 | 0.20 | 10.1 | 0.34 | 5.35 | 1.4 | 0.3373 | 1.3 | 0.93 |
| O31A2-1-105.2 Garnet | 4399 | 14918 | 11411 | 3.5 | 1248 | 1.1E-5 | 0.03 | 1.1 | 1.84 | 5.16 | 1.3 | 0.3480 | 1.3 | 0.94 |
| O31A2-2-104.1 Melanosome | 2235 | 32677 | 6202 | 15.1 | 649 | 6.0E-5 | 0.11 | 4.4 | 1.24 | 5.30 | 1.4 | 0.3379 | 1.3 | 0.96 |
| O31A2-1-021.2 Garnet | 895 | 34274 | 1213 | 39.6 | 256 | 9.5E-5 | 0.17 | 12.0 | 0.34 | 5.21 | 1.8 | 0.3480 | 1.3 | 0.94 |
| O31A2-2-104.2 Garnet | 2979 | 42927 | 11183 | 14.9 | 849 | 4.7E-5 | 0.08 | 4.3 | 0.68 | 5.21 | 1.8 | 0.3379 | 1.3 | 0.93 |
| O31A2-2-049.1 Garnet | 1961 | 37506 | 3397 | 19.8 | 568 | 4.9E-5 | 0.09 | 5.6 | 0.68 | 5.30 | 1.5 | 0.3450 | 1.3 | 0.99 |
| O31A2-1-130.2 Garnet | 3649 | 12516 | 12038 | 3.5 | 1039 | 2.0E-5 | 0.04 | 1.0 | 0.93 | 5.23 | 1.5 | 0.3314 | 1.5 | 0.99 |

Notes:
Uncertainties reported at 1σ.
Analytical details: mount IP829, 10 μm diameter spot, 0.5 nA O2− primary beam, 6 scans. Analysis name follows the convention w-x-y.z, where w = sample number, x = slide number, y = grain number and z = spot number. O31A2 was assigned GSC lab number 11861.

Abbreviations: f(206)204Pb refers to the mole percent of total 206Pb that is due to common Pb, calculated using the 204Pb-method; common Pb composition used is the surface blank (4/6: 0.05770; 7/6: 0.89500; 8/6: 2.13840).

*refers to radiogenic Pb (corrected for common Pb).

Disc. = Discordance given as difference between measured 206Pb/238U ratio and the expected 206Pb/238U ratio at t=207Pb/206Pb age, in percent.

U–Pb calibration/concentration reference material monazite 8153; U = 2065 ppm; 206Pb/238U age = 511.9 Ma (ID-TIMS, unpublished data, B. Davis); spot to spot error in 206Pb/238U calibration is 0.8% (included), standard error of the mean is 0.19% (not included, required when comparing data from different mounts). Analyses of two secondary monazite reference materials (2908 and 3345) were interspersed between the sample analyses to verify the accuracy of the Pb/Pb age. The measured weighted mean 207Pb/206Pb age of 2908 monazite was 1792.0 ± 4.8 Ma (n = 6), accepted age is 1795 Ma (Stern & Berman, 2000). The measured weighted mean 207Pb/206Pb age of 3345 monazite was 1817.7 ± 2.1 Ma (n = 14), accepted age is 1821 Ma (Stern & Berman, 2000).
Table S6 | Sample 18SAB-A27A2 U–Pb monazite data (GSC lab number z11850).

| Analysis position | Pb* (ppm) | 238U (ppm) | 206Pb (%) | 207Pb (%) | 204Pb ± 207Pb (%) | U (abs) | Pb (abs) (%) |
|-------------------|-----------|------------|---------|---------|------------------|--------|-------------|
| A27A2-1-120.2      | 29.4      | 12345     | 4.5    | 3.2    | 1.2E-5           | 6.4    | 0.37        |
| A27A2-1-049.1      | 31.2      | 12345     | 4.5    | 3.2    | 1.2E-5           | 6.4    | 0.37        |
| A27A2-2-049.1      | 31.2      | 12345     | 4.5    | 3.2    | 1.2E-5           | 6.4    | 0.37        |
| A27A2-1-120.1      | 29.4      | 12345     | 4.5    | 3.2    | 1.2E-5           | 6.4    | 0.37        |
| A27A2-1-027.2      | 31.2      | 12345     | 4.5    | 3.2    | 1.2E-5           | 6.4    | 0.37        |
| A27A2-1-100.2      | 29.4      | 12345     | 4.5    | 3.2    | 1.2E-5           | 6.4    | 0.37        |
| A27A2-2-048.1      | 31.2      | 12345     | 4.5    | 3.2    | 1.2E-5           | 6.4    | 0.37        |
| Notes:             |           |           |        |         |                  |        |             |

**Notes:**
- Uncertainties reported at 1σ.
- Primary beam, 6 scans. Analysis name follows the convention w-x-y.z, where w = sample number, x = slide number, y = grain number and z = Analytical details: mount IP829, 10
- Pb/* refers to radiogenic Pb (corrected for common Pb).
- 207Pb/206Pb age, in percent.
- U/Pb calibration/concentration reference material monazite 8153; U = 2065 ppm;
- U age = 511.9 Ma (ID-TIMS, unpublished data, B. Davis); spot to spot error in
- U calibration is 0.8% (included), standard error of the mean is 0.19% (not included, required when comparing data from different mounts). Analyses of two secondary monazite reference materials (2908 and 3345) were interspersed
Table S7 | LA-ICP-MS operating conditions.

| LA                  | Model                        | Photon Machines Analyte 193 |
|---------------------|------------------------------|-----------------------------|
| Wavelength          | 193 nm                       |                             |
| Pulse duration (FWHM) | 4 ns                         |                             |
| Sample cell         | Helex 2-volume cell, each with separate carrier gas-in port |                             |
| Smoothing device    | Not used                     |                             |

**Gas flows:**
1) He carrier into cup 0.6 L/min
2) He carrier into cell base 0.4 L/min
3) Ar make up 1.05–1.10 L/min

| ICP-MS               | Model                        | Agilent 7700x with additional interface rotary pump |
|---------------------|------------------------------|---------------------------------------------------|
| Shield torch        | Used                         |                                                   |
| Sampling depth       | 7 mm                         |                                                   |
| He collision gas     | 1 mL/min                     |                                                   |
| ThO\(^{+}\)/Th\(^{+}\) | < 0.3%                       |                                                   |
| U/Th sensitivity ratio (NIST 612) | 1.05–1.10 |                                                   |

**Data acquisition parameters for element mapping**

| Spot size and line spacing | 4 or 5 µm round spot (6 µm for NIST 610 only) |
|----------------------------|-----------------------------------------------|
| Line spacing               | 4 or 5 µm (6 µm for NIST 610 only)            |
| Sample translation speed   | 2.0 or 2.5 µm/s (3 µm/s for NIST 610 only)    |
| Pre-ablation cleaning      | 3 laser pulses per site (33 or 42 µm/s sample translation speed) |
| Laser repetition rate      | 25 Hz                                        |
| Energy density (fluence)   | 3.8 J/cm\(^2\)                             |

**Calibration standards:**
1) Elemental analysis NIST SRM 610 (doped, synthetic soda lime glass)
2) U–Pb age dating Monazite 2908

Isotopes measured (dwell time, ms)

\[
\begin{align*}
\text{27Al (2.0), } & \text{29Si (2.5), } \text{42Ca (2.0), } \text{57Fe (2.0),} \\
\text{89Y (2.0), } & \text{139La (2.0), } \text{140Ce (2.0), } \text{141Pr (2.0),} \\
\text{146Nd (2.0), } & \text{147Sm (2.0), } \text{151Eu (4.0), } \text{157Gd (2.0),} \\
\text{159Tb (2.0), } & \text{163Dy (2.0), } \text{165Ho (2.0), } \text{167Er (2.0),} \\
\text{169Tm (2.0), } & \text{173Yb (2.0), } \text{175Lu (2.0), } \text{206Pb (16.0),} \\
\text{207Pb (40.0), } & \text{208Pb (8.0), } \text{232Th (8.0), } \text{238U (8.0)}
\end{align*}
\]

Total mass sweep time 166.7 ms

Analysis time 20 s gas blank + up to 180 s ablation/line, up to 49 lines/map
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