

4. Analytical methods

4.1 Bulk composition of the vein

Six REE-rich vein samples were used for bulk rock major, minor, and trace element compositional analysis (ActLabs, Inc., Ontario, Canada). Prior to crushing, samples were trimmed with a saw to remove all surrounding aplitic material, leaving only the vein sample. Each sample was approximately 100g, and was crushed and prepared by ActLabs using a mild steel mill. The samples included five from veins, one of which consists of both core and rim combined (REE4), while the other four are of the core only (REE5-8). One additional allanite-(Ce)-rich sample was also analyzed from the southern locality (REE9). The analysis of major elements was obtained by fusion ICP, and trace elements by ICP (Ba, Be, Sc, Sr, V, Y, Zr) or ICP-MS (other trace elements). Fluorine was measured by ion-selective electrodes method.

4.2 Electron microprobe analysis

Mineral analyses and X-ray element mapping were performed on three samples (A2, A4, and B1) from the northern outcrop by WDS using a JEOL JXA-8600 electron microprobe at the University of Colorado-Boulder. It is a four-spectrometer instrument equipped with an argon X-ray detector (P-10 mixture) on spectrometer 1 and 2 (PET and TAP crystals), and xenon X-ray detector on spectrometers 3 and 4 (LiF crystals). Operating conditions using a W-cathode were 25 keV, and 20 nA beam current for most mineral phases. A higher current of 50 nA was used for allanite-(Ce) and uraninite to reduce the detection limits. A defocused beam (5 to 10 μm diameter) was used whenever possible for hydrous or fluorine bearing phases to minimize beam damage. No evidence of beam damage was observed under these conditions for all but the REE-carbonates. For these minerals, a 10 nA current and 10 μm beam diameter was used. A larger beam size was not possible for the REE-carbonates due to their small grain size, and a lower current would have increased the detection limit of several elements (especially HREE) to unacceptable levels. Details of the analytical setup including standards, X-ray lines, and analysis time for each element are listed in Supplementary Table 1a; beam current used for each analysis is provided with the complete analysis results (Supplementary Table 2). Background positions were adequately chosen to avoid interferences (Supplementary Table 1a). Peak interference corrections were applied for (1) Ce $M\zeta$ on F $K\alpha$, (2) Nd $L\alpha$ (II) on Cl $K\alpha$, (3) Dy $L\alpha$ on Eu $L\beta$, (4) Ho $L\alpha$ on Gd $L\beta$, (5) Tb $L\beta$ on Er $L\alpha$, (6) Sm $L\gamma$, Gd $L\beta_2$ and Dy $L\beta_{1,4}$ on Tm $L\alpha$, and (7) Th $M\zeta$ on U $M\beta$. The duration per analysis for each setup was 10 minutes (see Supplementary Table 1 for counting time for each element). Only analyses with totals between 98 and 102% were retained, except for the REE-carbonate for which a good analysis was difficult to obtain due to the small grain size and the high beam sensitivity. Values below detection limits were removed from the results.

4.3 Electron microprobe dating of monazite-(Ce) and uraninite

Additional monazite-(Ce) analyses were performed with the Cameca SX-100 “Ultrachron” at the University of Massachusetts, Amherst to obtain electron U-Th-Pb microprobe ages along with full quantitative analyses. Five individual crystals in two areas within the core zone #4 of sample A2 were selected. Analytical conditions were 15 keV, 200 nA beam current, focused beam diameter of 1 μm , and counting times for U, Pb and Th of 400, 500 and 250 seconds, respectively. In addition to U, Th and Pb, monazite-(Ce) analyses include Si, P, S, Ca, As, Y and REE (La to Nd and Sm to Yb). Uraninite analyses were obtained with a JEOL JXA-8600 instrument at the University of Colorado-Boulder, using a 50 nA beam current, a focused beam, and a similar setup for other element analysis as described above (Supplementary Table 1c). All major interference corrections for REE and actinide elements were applied to ensure accurate analysis, especially for U and Pb analysis (Th $M\gamma$ on U $M\beta$; Y $L\gamma$, La $L\alpha$ and Th $M\zeta$ on Pb $M\alpha$; see Allaz et al. 2013). U-Th-Pb dates were calculated based on the age equation from Montel et al. (1996) and decay constants from Steiger and Jäger (1977). Standardization and age calculations for monazite-(Ce) were checked for consistency before and after each analysis session using the standard Moacyr monazite. The 2σ errors reported include counting statistics and a 10% relative error on the background regression. Details of the monazite-(Ce) analysis setup can be found in Allaz et al. (2013), with the difference being that the multipoint background method was employed. This method permits precise determination of the background curvature and accurate measurement of the background under U $M\beta$, Th $M\alpha$ and Pb $M\alpha$ on monazite-(Ce) by measuring 3 to 5 backgrounds on either side of each peak (Supplementary Table 1b; Allaz et al., 2014). The background characterization for U-Th-Pb analysis in uraninite was less crucial, as all these elements are present as major elements; a classical two-point background acquisition was used with off-peak position adequately chosen to avoid background interferences.