# Supplementary information

### Sample details

Samples used were from the Natural History Museum, London, UK: collections BM1968 P37 and BM1957 1056, and are listed in Supplementary Table1 and Table 2.

**Supplementary Table 1**

Chilwa Island fenite samples. Last three samples used only for mineralogical investigation, and do not have whole-rock analyses

|  |  |  |
| --- | --- | --- |
| NHM number | NHM rock type classification | Fenite grade used in this study |
| BM1968 P37 63 | Quartz fenite | Medium |
| BM1968 P37 71 | Quartz fenite | Low |
| BM1968 P37 72 | Quartz fenite | Low |
| BM1968 P37 78 | Quartz fenite | Medium |
| BM1968 P37 83 | Quartz fenite | Not graded, probably high |
| BM1968 P37 96 | Quartz fenite | Medium |
| BM1968 P37 101 | Quartz fenite | Medium |
| BM1968 P37 130 | Quartz fenite | Low |
| BM1968 P37 32 | Syenite fenite | Medium |
| BM1968 P37 54 | Syenite fenite | Medium/high |
| BM1968 P37 68 | Syenite fenite | Medium/high |
| BM1968 P37 102 | Syenite fenite | Medium/high |
| BM1968 P37 139 | Breccia | Breccia |
| BM1968 P37 146 | Breccia | Breccia |
| BM1968 P37 100 | Quartz fenite | Medium |
| BM1968 P37 126 | Quartz fenite | Medium |
| BM1968 P37 137 | Syenite fenite | Medium/high |

**Supplementary Table 2**

a) Chilwa Island carbonatite samples used in whole-rock analyses

|  |  |
| --- | --- |
| NHM Number | NHM rock name |
| BM1957 1056 59 | Sövite |
| BM1957 1056 73 | Sövite |
| BM1957 1056 120 | Pyrochlore sövite |
| BM1957 1056 90 | Pyrochlore & ankerite in sövite |
| BM1968 P37 170 | Dolomitic/ankerite carbonatite |
| BM1957 1056 96 | Ankeritic carbonatite |
| BM1957 1056 94 | Ankeritic carbonatite |
| BM1957 1056 122 | Ankeritic carbonatite |
| BM1957 1056 114 | Sideritic carbonatite |
| BM1968 P37 172 | Sideritic & REE-rich carbonatite |

b) Chilwa Island carbonatite samples used for mineralogical investigation

|  |  |
| --- | --- |
| NHM Number | NHM rock name |
| BM1957 1056 102 | Ankeritic carbonatite |
| BM1957 1056 118 | Pyrochlore-rich carbonatite |
| BM1957 1056 128 | Pyrochlore-rich carbonatite |
| BM1957 1056 113 | Sideritic carbonatite |

**Methodology**

Back-scattered electron imaging (BSE), cathodoluminescence (CL) imaging and quantitative and mineral composition analyses were carried out at Kingston University on a Zeiss EVO 50 scanning electron microscope (SEM) and Oxford Instruments analytical suite (INCA) comprising an INCA X-act spectrometer and a CL Gatan Chroma-CL imager. The EDS operating conditions were an accelerating voltage of 20kV with a beam current of 1-1.8 nA. Spot size is controlled by the beam current and was approximately 5 µm. Calibration was made to a Co standard. Standards used are set out in Supplementary Table 3. Analyses of RE-bearing minerals are set out in Supplementary Tables 4-7.

**Supplementary Table 3** Standards used for SEM

|  |  |
| --- | --- |
| Element | Standard |
| F | Barium fluoride |
| Na | Jadeite |
| Mg | Periclase |
| Al | Corundum |
| P | Apatite |
| Cl | KCl |
| K | Orthoclase |
| Ca | Wollastonite |
| Ti | Ti metal |
| Fe | Fe metal |

Calibration standards for the REE are phosphate glasses, with a chemistry of (REE)P4, tested against a series of Drake and Weill (1972) REE glasses analyses, which yielded robust results.

Wavelength dispersive electron microprobe analyses of apatite and RE minerals were carried out using a JEOL JXA-8200 instrument at the Camborne School of Mines, University of Exeter. Operating conditions were an accelerating voltage of 20kV, a current of 28 nA and a 1 µm diameter beam size. TAP, PET and LIF, with a variety of natural mineral standards were used for calibration together with a ZAF matrix for background positions. Each element was measured for 20s on the peak and 10s on the background positions. The Pr L-beta line was used to avoid overlap with La. Background positions for the REE were adjusted to avoid overlaps and empirical correction factors were used for overlapping peaks. Fluorapatite was used as the calibration standard for Ca and P to minimise matrix effects and to reduce problems of overlap between P and F peaks. Detection limits were calculated as 3 standard deviations above background. Small spot size (5 µm) and a relatively high current were used to obtain reasonable analyses on very small minerals. Over 30 analyses of F were made to compensate for any crystal orientation effect. Element mapping of apatite was done at 20 kV, 33 nA and a 1 µm beam size.

Spatially resolved trace element determinations of a variety of apatites were obtained by Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICP-MS) on a New Wave UP193FX Laser Ablation System coupled to Agilent 7500cs ICP-MS at the Natural History Museum in London. NIST 612 was used as an external standard, and SiO2 as an internal standard, with Si values determined by SEM/EDS. Data were collected for 90s, using spot sizes of 20-30 µm, and laser fluence of 3.2J/cm2 firing at 10Hz. Analytical errors on this instrument are considered to be below 2-3%.

Whole rock analyses (Supplementary Table 8) were carried out at the Natural History Museum in London. Each sample was pre-treated with 1 ml concentrated HNO3, and then fused with 120 mg of LiBO2 in a Pt/Au crucible. Trace elements were measured by quadrupole inductively coupled mass spectrometry (ICP-MS). An aliquot of 100 mg of each sample was pre-treated with concentrated HNO3 and dissolved in a mixture of 4 ml HF and 1 ml HClO4 at 100˚C. This solution was dried down at 150˚C and the residue redissolved at 150˚C using 2 ml HClO4. The solution was again dried down, and then redissolved in a mixture of 1 ml concentrated HNO3 + 1 ml H2O + 0.5 H2O2 at 70˚C, and afterwards made up to 10 ml with water. Nonisobaric interferences in the ICP-MS analyses were reduced by tuning CeO/Ce+ to <1% and Ba2+/Ba+ to <1%. For Eu, Gd, Yb, Hf and W, the levels of polyatomic interferences were estimated using single-element standards and calculated concentrations were corrected accordingly. The concentration of Ga (using 71Ga) was corrected for 142REE++. Certified reference materials BCR-1, BHVO-1 (basalts, USGS standards), JG-1 (granodiorite, Geological Survey of Japan standard), JLS-1 (limestone, Geological Survey of Japan standard), GA (acid granite, CRPG standard), SY-3 (syenite, CCRMP standard), DNC-1 (dolerite, USGS standard) and MAG-1 (marine mud, USGS standard) were used to monitor the accuracy of all element analyses. Comparison with standards was made once per sampling run.

Loss on ignition (LOI) data was obtained at the Camborne School of Mines.

Raman spectroscopic analysis of double-polished wafer was carried out at Kingston University using a Renishaw RM1000 instrument with CCD detection via WIRE 1.3 software. A silicon standard with a single peak at 521 cm-1 was used, and runs were for 20s using a 514 nm Ar ion laser.

Microthermometry of fluid inclusions was performed at Kingston University, using a heating and cooling TMS600 mechanical stage attached to a Nikon Optiphot instrument, with a Tm94 Controller and Linksys 32 software. Calibration was made against synthetic fluid inclusion standards containing “pure” CO2 and H2O. The reported temperatures for the stage shoud be accurate to ± 2˚C for temperatures between 50˚C and 350˚C, ± 0.5˚C for temperatures between 0˚C and 50˚C, and ± 0.2˚C for temperatures between -60˚C and -1˚C.

### Supplementary Table 4 SEM-EDS analyses of apatite in fenite and carbonatite

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Low-grade  n=3 | SiO2 | CaO | SrO | Na2O | P2O5 | La2O3 | Ce2O3 | Pr2O3 | Nd2O3 | F | O = F | Total |
| Representative | 0.77 | 52.87 | 1.47 | 0.61 | 38.87 | 0.48 | 1.19 | n.d. | 0.64 | 3.58 | 1.51 | 98.97 |
| Std deviation | 0.40 | 0.90 | 0.24 | 0.42 | 0.21 | 0.11 | 0.12 |  | 0.10 | 0.47 |  |  |
| Medium-grade rim n=12 |  |  |  |  |  |  |  |  |  |  |  |  |
| Representative | 1.62 | 51.89 | 1.19 | 0.06 | 39.72 | 0.49 | 1.23 | 0.23 | 0.75 | 3.49 | 1.47 | 99.20 |
| Std deviation | 0.39 | 0.62 | 0.23 | 0.02 | 0.11 | 0.01 | 0.16 | 0.01 | 0.17 | 0.19 |  |  |
| Medium-grade core n=12 |  |  |  |  |  |  |  |  |  |  |  |  |
| Representative | 0.83 | 53.29 | 0.67 | 0.07 | 41.39 | 0.16 | 0.42 | 0.05 | 0.29 | 3.75 | 1.57 | 99.35 |
| Std deviation | 0.27 | 0.30 | 0.27 | 0.03 | 0.28 | 0.04 | 0.12 | 0.02 | 0.11 | 0.18 |  |  |
| Medium/high grade RE-rich n=15 |  |  |  |  |  |  |  |  |  |  |  |  |
| Representative | 1.04 | 50.17 | 2.53 | 0.75 | 39.73 | 1.10 | 2.00 | 0.16 | 0.57 | 3.42 | 1.44 | 100.03 |
| Std deviation | 0.31 | 0.22 | 0.92 | 0.11 | 0.64 | 0.37 | 0.39 | 0.08 | 0.12 | 0.43 |  |  |
| Medium/high grade RE-poor n=4 |  |  |  |  |  |  |  |  |  |  |  |  |
| Representative | n.d. | 52.90 | 2.79 | 0.53 | 40.78 | 0.48 | 1.15 | 0.15 | 0.45 | 2.42 | 1.02 | 100.63 |
| Std deviation |  | 2.13 | 0.81 | 0.24 | 0.77 | 0.09 | 0.04 | 0.09 | 0.15 | 0.79 |  |  |
| Carbonatite  n=7 |  |  |  |  |  |  |  |  |  |  |  |  |
| Representative | 0.63 | 52.18 | 2.73 | 0.22 | 40.97 | 0.13 | 0.36 | n.d. | 0.10 | 3.13 | 1.32 | 99.13 |
| Std deviation | 0.11 | 0.86 | 0.39 | 0.13 | 0.42 | 0.09 | 0.14 | n.d. | 0.07 | 0.67 |  |  |

Note: Y not analysed n.d. = not detected

### Supplementary Table 5 SEM-EDX analyses of monazite-(Ce) in fenite and carbonatite

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Low-grade  n=10 | SiO2 | FeO | CaO | SrO | P2O5 | Y2O3 | La2O3 | Ce2O3 | Pr2O3 | Nd2O3 | Sm2O3 | Gd2O3 | Dy2O3 | ThO2 | F | O = F | Total |
| Representative | n.d. | 1.11 | 1.29 | 0.66 | 28.72 | 1.28 | 15.79 | 33.05 | 3.21 | 12.14 | 1.32 | 1.20 | n.d. | 0.28 | 0.42 | 0.18 | 100.29 |
| Std deviation |  | 0.17 | 0.54 | 0.20 | 0.48 | 0.88 | 1.59 | 0.36 | 0.45 | 1.83 | 1.04 | 0.99 |  | 0.25 |  |  |  |
| Medium-grade  n=25 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Representative | 0.72 | 0.96 | 1.21 | 0.54 | 28.55 | n.a. | 15.27 | 32.33 | 3.05 | 12.30 | 1.19 | 0.92 | n.a. | 2.12 | n.d. |  | 99.16 |
| Std deviation | 0.48 | 0.63 | 0.52 | 0.51 | 1.43 |  | 2.97 | 2.02 | 0.56 | 2.56 | 0.69 | 0.47 |  | 1.48 |  |  |  |
| Rock 83 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Normal Ce | 0.80 | 2.20 | 3.80 | 0.29 | 28.15 | 6.71 | 12.47 | 17.69 | 2.45 | 9.38 | 1.74 | 1.59 | 1.11 | 5.74 | n.d. |  | 94.12 |
| Low Ce | 0.87 | 1.33 | 2.97 | 0.16 | 27.90 | 8.96 | 17.54 | 3.55 | 3.16 | 13.80 | 2.80 | 1.96 | 3.61 | 3.53 | n.d. |  | 92.14 |
| Carbonatite  n=2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Representative | 0.86 | n.d. | 1.51 | 3.43 | 28.46 | n.a. | 18.16 | 30.52 | 2.33 | 7.24 | 0.78 | 0.42 | n.a. | 4.91 | 0.13 | 0.05 | 98.70 |
| Std deviation | 0.85 |  | 0.60 | 0.06 | 0.23 |  | 0.15 | 0.81 | 0.20 | 0.12 | 0.32 | 0.40 |  | 0.26 | 0.12 |  |  |

Note: CO2 and HREE not analysed. HREE commonly ~2-3% in rock 83. 83 results are affected by mineral porosity and are considered to be semi-quantitative FeO = total iron n.d. = not detected n.a. = not analysed

### Supplementary Table 6 SEM-EDX analyses of bastnäsite-(Ce) in fenite and carbonatite

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Medium-grade n=7 | SiO2 | FeO | CaO | SrO | Y2O3 | La2O3 | Ce2O3 | Pr2O3 | Nd2O3 | Sm2O3 | Gd2O3 | Dy2O3 | ThO2 | F | O = F | Total |
| Representative | n.d. | 1.20 | 3.58 | 0.40 | n.a. | 19.74 | 28.30 | 2.58 | 9.03 | 1.48 | 1.06 | 0.60 | 1.79 | 10.84 | 4.56 | 76.04 |
| Std deviation |  | 0.76 | 0.57 | 0.35 |  | 2.92 | 1.25 | 0.70 | 2.26 | 1.07 | 0.57 | 0.44 | 0.72 | 1.54 |  |  |
| Rock 83  n=3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Representative | 1.80 | 1.04 | 3.02 | 0.49 | 2.70 | 10.21 | 34.30 | 2.05 | 6.04 | 1.23 | 0.79 | 0.94 | 9.99 | 7.25 | 3.05 | 78.80 |
| Std deviation | 1.06 | 0.95 | 0.70 | 0.18 | 0.56 | 6.26 | 17.77 | 1.03 | 3.48 | 0.56 | 0.72 | 0.16 | 2.19 | 0.56 |  |  |
| Ankeritic carbonatite n=6 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Representative | n.d. | 0.44 | 3.53 | 1.17 | n.a. | 22.91 | 31.48 | 1.89 | 5.44 | 0.25 | n.a. | n.a. | 2.31 | 11.43 | 4.81 | 76.04 |
| Std deviation |  | 0.39 | 2.50 | 0.33 |  | 1.43 | 2.97 | 0.49 | 1.04 | 0.11 |  |  | 1.82 | 0.06 |  |  |

Note: CO2 & HREE not analysed n.d. = not detected n.a. = not analysed

### Supplementary Table 7 SEM-EDX analyses of parisite-(Ce) in fenite and carbonatite

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Medium-grade n=8 | SiO2 | FeO | CaO | SrO | Y2O3 | La2O3 | Ce2O3 | Pr2O3 | Nd2O3 | Sm2O3 | Gd2O3 | Dy2O3 | ThO2 | F | O = F | Total |
| Representative | 0.73 | 0.80 | 12.61 | 1.33 | 0.97 | 11.09 | 21.48 | 2.30 | 9.24 | 1.57 | 0.96 | 0.82 | 3.25 | 9.74 | 4.10 | 72.79 |
| Std.deviation | 0.44 | 0.54 | 3.73 | 0.36 | 0.86 | 4.74 | 2.65 | 0.67 | 2.66 | 0.59 | 0.44 | 0.79 | 1.63 | 2.43 |  |  |
| Ankeritic carbonatite n=2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Representative | n.d. | 0.63 | 10.03 | 0.87 | n.a. | 18.89 | 27.05 | 1.81 | 5.64 | 0.39 | n.a. | n.a. | 0.73 | 11.03 | 4.64 | 72.43 |
| Std.deviation |  | 0.59 | 1.47 | 0.14 |  | 3.51 | 0.85 | 0.30 | 0.93 | 0.10 |  |  | 0.27 | 1.95 |  |  |

Note: CO2 & HREE not analysed n.d. = not detected n.a. = not analysed

### Supplementary Table 8 Whole rock analysis of fenite

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| BM1968 P37 | 72 | 130 | 71 | 32 | 63 | 78 | 96 | 101 | 54 | 68 | 102 | 139 | 146 | 83 |
| Majors % |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| SiO2 | 71.73 | 72.90 | 68.80 | 63.98 | 62.34 | 63.37 | 62.62 | 60.74 | 62.53 | 58.55 | 61.75 | 62.40 | 60.57 | 86.21 |
| TiO2 | 0.08 | 0.12 | 0.24 | 1.21 | 1.16 | 1.03 | 1.18 | 1.15 | 0.90 | 1.02 | 0.80 | 0.09 | 0.04 | 0.07 |
| Al2O3 | 15.87 | 13.53 | 14.39 | 13.49 | 13.75 | 13.96 | 14.57 | 13.13 | 14.14 | 12.61 | 13.56 | 16.55 | 16.44 | 0.49 |
| Fe2O3 (t) | 1.31 | 1.78 | 1.83 | 5.05 | 6.91 | 5.80 | 6.82 | 6.44 | 6.19 | 6.18 | 5.94 | 1.46 | 1.72 | 1.93 |
| MnO | 0.01 | 0.05 | 0.06 | 0.12 | 0.08 | 0.09 | 0.09 | 0.13 | 0.16 | 0.29 | 0.12 | 0.03 | 0.01 | 0.10 |
| MgO | 0.06 | 0.14 | 0.14 | 1.02 | 0.79 | 0.74 | 0.81 | 0.95 | 0.40 | 0.94 | 0.81 | 0.01 | 0.01 | 0.02 |
| CaO | 1.35 | 1.53 | 0.47 | 2.68 | 2.27 | 2.55 | 3.26 | 3.12 | 1.60 | 4.52 | 2.84 | 1.04 | 2.21 | 1.95 |
| Na2O | 4.25 | 6.13 | 3.35 | 5.19 | 3.88 | 4.09 | 4.46 | 4.62 | 5.77 | 5.18 | 5.29 | 0.22 | 0.27 | 0.05 |
| K2O | 5.75 | 2.14 | 7.58 | 5.30 | 4.88 | 5.19 | 5.15 | 4.86 | 6.00 | 6.30 | 5.50 | 14.08 | 13.60 | 0.05 |
| P2O5 | 0.13 | 0.04 | 0.06 | 0.33 | 0.39 | 0.32 | 0.37 | 0.34 | 0.26 | 0.39 | 0.36 | 0.94 | 1.84 | 1.64 |
| BaO | 0.08 | 0.05 | 0.52 | 0.23 | 0.41 | 0.37 | 0.26 | 0.34 | 0.43 | 0.30 | 0.27 | 0.11 | 0.26 | 0.11 |
| SrO | 0.04 | 0.02 | 0.03 | 0.06 | 0.05 | 0.05 | 0.05 | 0.09 | 0.04 | 0.08 | 0.06 | 0.14 | 0.09 | 0.10 |
| LOI | 0.67 | 0.59 | 0.72 | 0.95 | 0.66 | 1.26 | 1.10 | 1.79 | 1.07 | 2.24 | 2.13 | 0.57 | 0.69 | 0.94 |
| Total | 101.34 | 99.024 | 98.19 | 99.61 | 97.571 | 98.82 | 100.74 | 97.70 | 99.50 | 98.59 | 99.44 | 97.64 | 97.77 | 93.66 |

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| F ppm | 262 | 414 | 209 | 1167 | 523 | 1091 | 969 | 1303 | 1809 | 4181 | 2457 | 869 | 1521 | 2285 |
| Cl ppm | 250 | 177 | 187 | 167 | 292 | 182 | 217 | 187 | 247 | 203 | 205 | 114 | 116 | n.d. |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Traces ppm | 72 | 130 | 71 | 32 | 63 | 78 | 96 | 101 | 54 | 68 | 102 | 139 | 146 | 83 |
| Li | 3.8 | 6.5 | 8.2 | 10.3 | 5.9 | 10.5 | 17.6 | 18.5 | 8.5 | 7.5 | 32.5 | 0.6 | 0.7 | 17.0 |
| S | 75.0 | 77.4 | 690.0 | 107.0 | 432.0 | 302.0 | 142.5 | 1184.6 | 644.0 | 197.0 | 255.0 | 294.0 | 139.0 | 749.0 |
| V | 23.4 | 6.9 | 41.3 | 27.6 | 49.0 | 35.4 | 56.3 | 97.6 | 99.8 | 216.8 | 51.7 | 46.8 | 47.5 | 72.2 |
| Co | 1.6 | 1.8 | 2.6 | 6.9 | 7.4 | 7.1 | 23.8 | 8.8 | 5.3 | 7.0 | 7.2 | 2.7 | 2.1 | 3.6 |
| Cu | 2.1 | 0.3 | 0.4 | 9.6 | 14.8 | 3.2 | 7.5 | 4.8 | 7.3 | 6.9 | 7.9 | 3.3 | 1.8 | 171.5 |
| Zn | 16.3 | 49.6 | 42.8 | 90.9 | 105.0 | 104.0 | 121.0 | 142.8 | 108.0 | 162.0 | 112.0 | 16.3 | 20.7 | 62.4 |
| Ga | 21.4 | 19.1 | 18.8 | 18.3 | 21.6 | 22.5 | 28.4 | 22.1 | 22.2 | 18.9 | 20.4 | 54.7 | 33.7 | n.d. |
| Rb | 132.4 | 31.0 | 187.3 | 105.4 | 81.2 | 87.0 | 85.3 | 86.0 | 93.5 | 99.3 | 86.2 | 198.9 | 224.1 | 1.1 |
| Y | 8.1 | 23.5 | 60.8 | 51.5 | 46.5 | 49.6 | 67.3 | 54.3 | 38.2 | 38.6 | 37.3 | 65.7 | 134.8 | 339.7 |
| Zr | 48.5 | 100.7 | 313.7 | 1000.0 | 1175.0 | 1238.0 | 52.5 | 1097.0 | 960.2 | 466.1 | 920.5 | 112.8 | 843.1 | 21.0 |
| Nb | 1.9 | 10.0 | 48.5 | 82.9 | 39.8 | 45.4 | 39.5 | 85.3 | 58.4 | 71.1 | 62.3 | 59.8 | 895.0 | 22.9 |
| Mo | 0.8 | 0.7 | 8.4 | 2.3 | 3.0 | 4.4 | 3.6 | 6.4 | 12.1 | 9.9 | 8.7 | 31.1 | 2.0 | 10.4 |
| Hf | 1.7 | 0.6 | 1.5 | 5.0 | 0.5 | 1.2 | 1.5 | 2.6 | 9.9 | 10.7 | 5.0 | 2.0 | 0.8 | 0.2 |
| Ta | 0.1 | 0.5 | 0.9 | 4.5 | 1.6 | 2.7 | 1.6 | 2.9 | 0.9 | 1.9 | 1.8 | 0.7 | 16.2 | n.d. |
| W | 0.6 | 0.5 | 1.0 | 2.3 | 3.8 | 1.8 | 155.8 | 2.4 | 3.4 | 1.9 | 6.7 | 1.1 | 6.9 | 0.4 |
| Pb | 24.5 | 10.8 | 29.1 | 34.3 | 18.9 | 17.6 | 14.0 | 23.1 | 85.2 | 39.7 | 25.1 | 14.9 | 6.0 | 263.2 |
| Th | 1.6 | 2.7 | 7.1 | 11.0 | 2.3 | 5.0 | 4.0 | 6.2 | 24.2 | 9.2 | 9.8 | 32.6 | 76.0 | 280.0 |
| U | 0.6 | 0.2 | 1.1 | 1.8 | 0.4 | 0.6 | 0.4 | 0.4 | 0.9 | 0.5 | 0.6 | 5.1 | 10.9 | 20.3 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| REE ppm | 72 | 130 | 71 | 32 | 63 | 78 | 96 | 101 | 54 | 68 | 102 | 139 | 146 | 83 |
| La | 15.0 | 17.9 | 91.8 | 85.7 | 53.3 | 51.6 | 53.1 | 118.4 | 79.1 | 79.9 | 126.1 | 14.1 | 102.3 | 483.5 |
| Ce | 30.8 | 37.6 | 138.0 | 170.0 | 122.0 | 100.5 | 126.3 | 164.0 | 145.3 | 164.0 | 215.6 | 22.5 | 158.7 | 786.2 |
| Pr | 3.5 | 4.2 | 19.6 | 21.2 | 18.2 | 13.6 | 17.9 | 22.7 | 18.4 | 20.6 | 24.8 | 2.5 | 16.7 | 88.1 |
| Nd | 12.4 | 15.7 | 69.0 | 84.4 | 82.2 | 55.4 | 69.0 | 79.2 | 72.2 | 80.8 | 96.1 | 9.8 | 58.5 | 312.6 |
| Sm | 2.5 | 3.0 | 10.8 | 16.7 | 17.6 | 10.0 | 17.3 | 12.7 | 14.6 | 15.3 | 16.8 | 4.2 | 18.8 | 64.3 |
| Eu | 1.0 | 0.6 | 4.1 | 3.9 | 4.8 | 3.9 | 4.5 | 4.2 | 4.7 | 4.8 | 4.7 | 2.2 | 8.6 | 21.2 |
| Gd | 2.4 | 2.8 | 9.9 | 14.8 | 15.6 | 9.6 | 15.7 | 12.0 | 12.1 | 12.8 | 12.9 | 8.3 | 33.7 | 67.4 |
| Tb | 0.3 | 0.4 | 1.4 | 2.3 | 2.3 | 1.4 | 2.2 | 1.6 | 1.8 | 1.8 | 1.8 | 1.7 | 6.4 | 11.5 |
| Dy | 1.5 | 2.4 | 7.0 | 12.1 | 11.9 | 7.2 | 11.5 | 8.2 | 9.4 | 9.4 | 8.7 | 11.7 | 34.5 | 71.2 |
| Ho | 0.3 | 0.5 | 1.4 | 2.3 | 2.1 | 1.3 | 2.1 | 1.5 | 1.7 | 1.7 | 1.6 | 2.5 | 5.7 | 12.7 |
| Er | 0.8 | 1.7 | 3.8 | 6.3 | 5.5 | 3.7 | 5.8 | 4.0 | 4.6 | 4.7 | 4.1 | 7.4 | 13.6 | 32.6 |
| Tm | 0.1 | 0.3 | 0.5 | 0.8 | 0.7 | 0.5 | 0.8 | 0.5 | 0.6 | 0.7 | 0.6 | 0.9 | 1.6 | 4.0 |
| Yb | 0.6 | 1.8 | 2.9 | 5.2 | 4.0 | 2.9 | 4.2 | 3.0 | 4.1 | 4.6 | 3.8 | 4.7 | 8.5 | 21.7 |
| Lu | 0.1 | 0.3 | 0.4 | 0.8 | 0.5 | 0.4 | 0.7 | 0.4 | 0.6 | 0.7 | 0.6 | 0.6 | 1.1 | 2.6 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| La/Yb | 25 | 10 | 32 | 16 | 13 | 18 | 13 | 39 | 19 | 17 | 33 | 3 | 12 | 22 |

Hf, Nb, Ta and Th may be low due to incomplete digestion