# Supplementary information

### Sample details

Samples used were from the Natural History Museum, London, UK: collections BM1968 P37, BM1957 and 1056. The collections referred to in Wall (2000) are from BM1993 P4 and BM1993. Samples are listed in Supplementary Table1 and Table 2.

**Table S1**

a) 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 |

b) Kangankunde fenite samples. The last sample used only for mineralogical investigation and does not have a whole-rock analysis

|  |  |  |
| --- | --- | --- |
| **NHM number** | **NHM rock type classification** | **Fenite grade used in this study** |
| BM1968 P37 187 | Quartz fenite | Medium |
| BM1968 P37 193 | Quartz fenite | Low |
| BM1968 P37 201 | Quartz fenite | Low |
| BM1968 P37 218 | Quartz fenite | Low |
| BM1968 P37 242 | Quartz fenite | Medium |
| BM1968 P37 250 | Quartz fenite | Low |
| BM1968 P37 279 | Quartz fenite | Medium |
| BM1968 P37 198 | Syenite fenite | Medium |
| BM1968 P37 209 | Syenite fenite | Low |
| BM1968 P37 249 | Syenite fenite | Low |
| BM1968 P37 273 | Syenite fenite | Medium |
| BM1968 P37 212 | Breccia | Breccia |
| BM1968 P37 254 | Breccia | Breccia |
| BM1968 P37 278 | Quartz fenite | Medium |

**Table S2**

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 |

c) Kangankunde carbonatite samples from Wall (2000)

|  |  |  |
| --- | --- | --- |
| **NHM Number** | **Carbonatite type at complex** | **Additional description (Wall 2000)** |
| BM1993 P4(1) | Main carbonatite | Ankerite, RE-rich |
| BM1993 P4(9) | Main carbonatite | Dark, RE-rich |
| BM1993 P4(15) | Main carbonatite | Fe- and RE-rich |
| BM1993 P4(19) | Main carbonatite | Sideritic(?) RE-rich vein |
| BM1993 73(87) | Main carbonatite | Dolomitic, RE-rich |
| BM1993 73(77) | Main carbonatite | Sideritic RE-rich vein |
| BM1993 73(100) | Main carbonatite | Leucocratic/sideritic, RE-rich |
| BM1993 P4(5) | Main carbonatite | RE-poor rock with monazite |
| BM1993 P4(28) | Main carbonatite | Dark, RE-poor |
| BM1993 73(77) | Main carbonatite | Sideritic/ankeritic/dolomitic RE-poor (host) |
| BM1993 P4(19) | Main carbonatite | Mid-brown, RE-poor (host) |
| BM1993 73(50) | Apatite-dolomitic carbonatite |  |
| BM1993 73(58) | Apatite-dolomitic carbonatite |  |
| BM1993 73(59) | Phlogopitic apatite dolomitic 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. A cobalt standard was used to standardise between analyses made on different days and to check consistency of beam conditions during the day. A standard Na-plagioclase was also analysed at intervals to check the quality of results Analyses of RE-bearing minerals are set out in Supplementary Tables 4-7.

**Table S3** 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.

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.

**Table S4** Apatite analyses (from RE-bearing zones of grains)

a) Chilwa Island

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Low-grade fenite*N* = 3 | Medium-grade fenite*N* = 12 | Medium/high-gradefenite*N* = 15 | Sövite*N* = 7 |
|  | average | std dev | average | std dev | average | std dev | average | std dev |
| SiO2 | 0.77 | 0.40 | 1.62 | 0.39 | 1.04 | 0.31 | 0.63 | 0.11 |
| CaO | 52.87 | 0.90 | 51.89 | 0.62 | 50.17 | 0.22 | 52.18 | 0.86 |
| SrO | 1.47 | 0.24 | 1.19 | 0.23 | 2.53 | 0.92 | 2.73 | 0.39 |
| Na2O | 0.61 | 0.42 | 0.06 | 0.02 | 0.75 | 0.11 | 0.22 | 0.13 |
| P2O5 | 38.87 | 0.21 | 39.72 | 0.11 | 39.73 | 0.64 | 40.97 | 0.42 |
| La2O3 | 0.48 | 0.11 | 0.49 | 0.01 | 1.10 | 0.37 | 0.13 | 0.09 |
| Ce2O3 | 1.19 | 0.12 | 1.23 | 0.16 | 2.00 | 0.39 | 0.36 | 0.14 |
| Pr2O3 | 0.33 | 0.16 | 0.23 | 0.01 | 0.16 | 0.08 | n.d. |  |
| Nd2O3 | 0.64 | 0.10 | 0.75 | 0.17 | 0.57 | 0.12 | 0.10 | 0.07 |
| F | 3.58 | 0.47 | 3.49 | 0.19 | 3.42 | 0.43 | 3.13 | 0.67 |
| O=F | 1.51 |  | 1.47 | 1.58 | 1.44 |  | 1.32 |  |
| Total | 99.30 |  | 99.20 |  | 100.03 |  | 99.13 |  |

b) Kangankunde

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Low-grade fenite*N* = 13 | Medium-grade fenite*N* = 7 | Apatite-dolomite carbonatite*N* = 4 | Quartz-apatite rock*N* = 4 |
|  | average | std dev | average | std dev | average | std dev | average | std dev |
| SiO2 |  |  |  |  | 0.52 | 0.29 | 0.11 | 0.05 |
| CaO | 49.28 | 2.60 | 47.55 | 2.60 | 53.26 | 1.36 | 50.78 | 0.57 |
| SrO | 2.89 | 1.24 | 4.50 | 1.10 | 2.57 | 0.41 | 3.07 | 0.64 |
| Na2O | 1.99 | 0.36 | 2.28 | 0.19 | 0.10 |  | 0.66 | 0.45 |
| P2O5 | 38.15 | 0.67 | 36.59 | 1.60 | 40.09 | 0.64 | 39.22 | 0.57 |
| La2O3 | 0.74 | 0.50 | 1.54 | 1.29 | 0.15 | 0.05 | 0.11 | 0.05 |
| Ce2O3 | 2.59 | 0.98 | 3.13 | 0.57 | 0.34 | 0.16 | 0.80 | 0.58 |
| Pr2O3 | 0.46 | 0.24 | 0.57 | 0.24 | n.a. |  | n.a. |  |
| Nd2O3 | 2.10 | 1.01 | 2.16 | 0.81 | 0.16 | 0.09 | 0.92 | 0.12 |
| Sm2O3 | n.a. |  | 0.74 | 0.12 |  |  | 0.23 |  |
| F | 3.60 | 0.30 | 3.66 |  | 3.25 | 0.17 | 4.15 | 2.40 |
| O=F | 1.52 |  | 1.54 |  | 1.37 |  | 1.75 |  |
| Total | 100.28 |  | 101.18 |  | 99.07 |  | 98.30 |  |

CO2 and HREE not analysed. FeO = total iron; n.a. = not analysed; n.d. = not detected

Kangankunde carbonatite mineral analysis is from Wall (2000)

**Table S5** Monazite analyses

a) Chilwa Island

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Low-grade fenite*N* = 10 | Medium-grade fenite*N* = 25 | Rock BM1968 P37 83 | Ankerite*N* = 2 |
|  | average | std dev | average | std dev | Ce-bearing | low CE | average | std dev |
| SiO2 | n.d. |  | 0.72 | 0.48 | 0.80 | 0.87 | 0.86 | 0.85 |
| FeO | 1.11 | 0.17 | 0.96 | 0.63 | 2.20 | 1.33 | n.d. |  |
| CaO | 1.29 | 0.54 | 1.21 | 0.52 | 3.80 | 2.97 | 1.51 | 0.85 |
| SrO | 0.66 | 0.20 | 0.54 | 0.51 | 0.29 | 0.16 | 3.43 | 0.06 |
| P2O5 | 28.72 | 0.48 | 28.55 | 1.43 | 28.15 | 27.90 | 28.46 | 0.23 |
| Y2O3 | 1.28 | 0.88 | n.a. |  | 6.71 | 8.96 | n.a. |  |
| La2O3 | 15.79 | 1.59 | 15.27 | 2.97 | 12.47 | 17.54 | 18.16 | 0.15 |
| Ce2O3 | 33.05 | 0.36 | 32.33 | 2.02 | 17.69 | 3.55 | 30.52 | 0.81 |
| Pr2O3 | 3.21 | 0.45 | 3.05 | 0.56 | 2.45 | 3.16 | 2.33 | 0.20 |
| Nd2O3 | 12.14 | 1.83 | 12.30 | 2.56 | 9.38 | 13.80 | 7.24 | 0.12 |
| Sm2O3 | 1.32 | 1.04 | 1.19 | 0.69 | 1.74 | 2.80 | 0.78 | 0.32 |
| Gd2O3 | 1.20 | 0.99 | 0.92 | 0.47 | 1.59 | 1.96 | 0.42 | 0.40 |
| Dy2O3 | n.d. |  | n.a. |  | 1.11 | 3.61 | n.a. |  |
| Th2O3 | 0.28 | 0.25 | 2.12 | 1.48 | 5.74 | 3.53 | 4.91 | 0.26 |
| F | 0.42 |  | n.d. |  | n.d. | n.d. | 0.13 | 0.12 |
| O=F | 0.18 |  |  |  |  |  | 0.05 |  |
| Total | 100.29 |  | 99.16 |  | 94.12 | 92.14 | 98.70 |  |

HREE are commonly 2-3% in rock BM1968 P37 83. Results are affected by mineral porosity and are considered to be semiquantitative.

b) Kangankunde

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Low-grade fenite*N* = 8 | Medium-grade fenite*N* = 15 | Breccia*N* = 6 | Apatite-dolomite carbonatite*N* = 3 | Main REE carbonatite*N* = 5 | Quartz-monazite rock*N* = 5 |
|  | average | std dev | average | std dev | average | std dev | average | std dev | average | std dev | average | stddev |
| SiO2 | n.d. |  | n.d. |  | n.d. |  | n.d. |  | n.d. |  | 0.18 | 0.04 |
| FeO | n.d. |  | 1.32 | 0.61 | n.d. |  | n.a. |  | n.a |  | n.a. |  |
| CaO | 0.78 | 0.54 | 0.36 | 0.10 | 0.41 | 0.26 | 1.56 | 1.18 | 0.38 | 0.11 | 0.17 | 0.02 |
| SrO | 2.25 | 0.69 | 2.64 | 0.75 | 1.70 | 0.23 | 1.53 | 0.39 | 1.93 | 0.69 | 1.58 | 0.12 |
| P2O5 | 28.97 | 0.56 | 29.50 | 1.38 | 29.70 | 0.48 | 30.28 | 1.19 | 30.41 | 0.96 | 29.97 | 0.37 |
| La2O3 | 11.62 | 1.80 | 12.67 | 2.64 | 16.27 | 1.06 | 19.33 | 4.73 | 22.27 | 3.05 | 18.20 | 2.55 |
| Ce2O3 | 30.02 | 1.87 | 32.37 | 2.35 | 34.13 | 0.66 | 36.51 | 4.40 | 34.89 | 0.89 | 35.26 | 1.06 |
| Pr2O3 | 3.70 | 0.28 | 3.50 | 0.46 | 3.07 | 0.32 | 2.30 | 1.05 | 2.38 | 0.39 | 3.29 | 0.36 |
| Nd2O3 | 16.36 | 2.94 | 13.75 | 2.22 | 11.87 | 1.08 | 7.89 | 2.60 | 7.57 | 1.32 | 10.07 | 1.80 |
| Sm2O3 | 2.05 | 0.62 | 1.09 | 0.45 | 0.73 | 0.06 | 0.79 |  | 0.38 | 0.15 | 0.88 | 0.34 |
| Gd2O3 | 1.12 | 0.99 | 0.80 | 0.14 | 0.51 | 0.10 | n.d. |  | n.d. |  | 0.37 | 0.13 |
| Dy2O3 | n.d. |  | n.a. |  | 1.11 | 3.61 | n.a. |  | n.a. |  | n.a. |  |
| Th2O3 | 2.26 | 1.51 | 1.02 | 0.61 | 0.78 | 0.18 | n.a. |  | n.a. |  | n.a. |  |
| F | n.d. |  | 0.66 | 0.48 | 0.20 | 0.01 | n.a. |  | n.a. |  | n.a. |  |
| O=F |  |  | 0.27 |  | 0.08 |  |  |  |  |  |  |  |
| Total | 99.13 |  | 99.41 |  | 100.40 |  | 100.19 |  | 100.21 |  | 99.97 |  |

CO2 and HREE not analysed. FeO = total iron; n.a. = not analysed; n.d. = not detected

Kangankunde carbonatite mineral analysis is from Wall (2000)

**Table S6** Bastnäsite analyses

a) Chilwa Island

|  |  |  |  |
| --- | --- | --- | --- |
|  | Medium-grade fenite*N* = 7 | Rock BM1968 P37 83*N* = 3 | Ankerite*N* = 6 |
|  | average | std dev | average | std dev | average | std dev |
| SiO2 | n.d. |  | 1.80 | 1.06 | n.d. |  |
| FeO | 1.20 | 0.76 | 1.04 | 0.95 | 0.44 | 0.39 |
| CaO | 3.58 | 0.57 | 3.02 | 0.70 | 3.53 | 2.50 |
| SrO | 0.40 | 0.35 | 0.49 | 0.18 | 1.17 | 0.33 |
| Y2O3 | n.a. |  | 2.70 | 0.56 | n.a. |  |
| La2O3 | 19.74 | 2.92 | 10.21 | 6.26 | 22.91 | 1.43 |
| Ce2O3 | 28.30 | 1.25 | 34.30 | 17.77 | 31.48 | 2.97 |
| Pr2O3 | 2.58 | 0.70 | 2.05 | 1.03 | 1.89 | 0.49 |
| Nd2O3 | 9.03 | 2.26 | 6.04 | 3.48 | 5.44 | 1.04 |
| Sm2O3 | 1.48 | 1.07 | 1.23 | 0.56 | 0.25 | 0.11 |
| Gd2O3 | 1.06 | 0.57 | 0.79 | 0.72 | n.a. |  |
| Dy2O3 | 0.60 | 0.44 | 0.94 | 0.16 | n.a. |  |
| Th2O3 | 1.79 | 0.72 | 9.99 | 2.19 | 2.31 | 1.82 |
| F | 10.84 | 1.54 | 7.25 | 0.56 | 11.43 | 0.06 |
| O=F | 4.56 |  | 3.05 |  | 4.81 |  |
| Total | 76.04 |  | 78.80 | 92.14 | 76.04 |  |

b) Kangankunde

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Low-grade fenite*N* = 8 | Medium-grade fenite*N* = 11 | Breccia*N* = 4 | Apatite-dolomite carbonatite*N* = 1 | Main REE carbonatite*N* = 2 | Quartz-monazite rock*N* = 1 |
|  | average | std dev | average | std dev | average | std dev |  | average | std dev |  |
| SiO2 | n.d. |  | n.d. |  | n.d. |  | 0.30 | 0.35 | 0.07 | 0.40 |
| CaO | 1.68 | 0.87 | 0.98 | 0.61 | 0.91 | 0.35 | 0.60 | 0.40 | 0.14 | 0.30 |
| SrO | 1.29 | 0.58 | 2.09 | 0.92 | 1.08 | 0.43 | 0.80 | 0.50 | 0.14 | 0.50 |
| La2O3 | 8.98 | 0.58 | 14.46 | 1.29 | 17.33 | 3.11 | 22.60 | 26.50 | 1.70 | 23.10 |
| Ce2O3 | 30.78 | 0.71 | 32.93 | 1.39 | 32.93 | 0.72 | 32.80 | 30.35 | 1.34 | 33.40 |
| Pr2O3 | 3.63 | 0.44 | 3.50 | 0.25 | 2.99 | 0.33 | 1.50 | 2.35 | 0.35 | 3.20 |
| Nd2O3 | 17.85 | 1.58 | 12.69 | 1.60 | 10.48 | 2.25 | 7.80 | 6.35 | 1.06 | 7.80 |
| Sm2O3 | 1.58 | 0.36 | 0.83 | 0.34 | 0.44 | 0.21 | n.a. | n.a. |  | n.a. |
| Gd2O3 | n.d. |  | 0.58 | 0.24 | n.d |  | n.a. | n.a. |  | n.a. |
| F | 9.70 | 0.55 | 9.34 | 0.45 | 9.34 |  | n.a. | n.a. |  | n.a. |
| O=F | 4.08 |  | 3.93 |  | 3.93 |  |  |  |  |  |
| Total | 71.41 |  | 73.47 |  | 71.57 |  | 66.40 | 66.80 |  | 68.70 |

CO2 and HREE not analysed. FeO = total iron; n.a. = not analysed; n.d. = not detected

Kangankunde carbonatite mineral analysis is from Wall (2000)

**Table S7** Parisite analyses

a) Chilwa Island

|  |  |  |
| --- | --- | --- |
|  | Medium-grade fenite*N* = 8 | Ankerite*N* = 3 |
|  | average | std dev | average | std dev |
| SiO2 | 0.73 | 0.44 | n.d. |  |
| FeO | 0.80 | 0.54 | 0.63 | 0.59 |
| CaO | 12.61 | 3.73 | 10.03 | 1.47 |
| SrO | 1.33 | 0.36 | 0.87 | 0.14 |
| Y2O3 | 0.97 | 0.86 | n.a. |  |
| La2O3 | 11.09 | 4.74 | 18.89 | 3.51 |
| Ce2O3 | 21.48 | 2.65 | 27.05 | 0.85 |
| Pr2O3 | 2.30 | 0.67 | 1.81 | 0.30 |
| Nd2O3 | 9.24 | 2.66 | 5.64 | 0.93 |
| Sm2O3 | 1.57 | 0.59 | 0.39 | 0.10 |
| Gd2O3 | 0.96 | 0.44 | n.a. |  |
| Dy2O3 | 0.82 | 0.79 | n.a. |  |
| Th2O3 | 3.25 | 1.63 | 0.73 | 0.27 |
| F | 9.74 | 2.43 | 11.03 | 1.95 |
| O=F | 4.10 |  | 4.64 |  |
| Total | 72.79 |  | 72.43 |  |

b) Kangankunde

|  |  |  |
| --- | --- | --- |
|  | Low-grade fenite*N* = 3 | Medium-grade fenite*N* = 13 |
|  | average | std dev | average | std dev |
| SiO2 | n.d. |  | n.d. |  |
| FeO | n.d. |  | n.d. |  |
| CaO | 12.32 | 3.80 | 13.28 | 5.03 |
| SrO | 1.27 | 0.49 | 1.81 | 0.70 |
| Y2O3 | n.a. |  | n.a. |  |
| La2O3 | 9.77 | 0.83 | 11.14 | 1.77 |
| Ce2O3 | 26.61 | 2.29 | 27.62 | 3.10 |
| Pr2O3 | 3.16 | 0.39 | 2.79 | 0.43 |
| Nd2O3 | 13.72 | 0.73 | 11.55 | 1.69 |
| Sm2O3 | 1.35 | 0.27 | 1.12 | 0.45 |
| Gd2O3 | 0.63 | 0.12 | n.d. |  |
| Dy2O3 | n.a | n.a. | n.a. |  |
| Th2O3 | n.d. |  | n.d. |  |
| F | 7.33 | 0.50 | 7.12 | 0.76 |
| O=F | 3.09 |  | 2.99 |  |
| Total | 73.07 |  | 73.55 |  |

CO2 and HREE not analysed. FeO = total iron; n.a. = not analysed; n.d. = not detected

### Table S8 Whole rock analysis of fenite

1. Chilwa Island

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 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. |

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 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 |

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 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 |

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

b) Kangankunde

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| BM1968 P37 | 193 | 201 | 209 | 249 | 218 | 250 | 187 | 198 | 242 | 273 | 279 | 212 | 254 |
| Majors % |  |  |  |  |  |  |  |  |  |  |  |  |  |
| SiO2 | 69.89 | 67.72 | 59.14 | 56.60 | 64.08 | 59.99 | 57.37 | 51.60 | 51.72 | 58.89 | 58.91 | 41.13 | 26.60 |
| TiO2 | 0.22 | 0.32 | 0.36 | 1.08 | 0.55 | 0.39 | 0.30 | 0.47 | 0.74 | 0.50 | 0.98 | 0.15 | 0.22 |
| Al2O3 | 13.02 | 11.05 | 12.54 | 13.83 | 13.22 | 11.99 | 11.97 | 9.64 | 12.79 | 11.59 | 13.49 | 7.62 | 7.07 |
| Fe2O3 (t) | 3.62 | 4.51 | 6.08 | 6.80 | 4.47 | 9.87 | 6.83 | 12.16 | 7.76 | 12.83 | 7.78 | 9.57 | 11.69 |
| MnO | 0.13 | 0.18 | 0.24 | 0.25 | 0.14 | 0.12 | 0.60 | 0.37 | 0.42 | 0.34 | 0.30 | 0.83 | 2.28 |
| MgO | 0.19 | 0.88 | 1.83 | 1.15 | 1.02 | 0.99 | 2.92 | 4.03 | 2.08 | 0.45 | 2.15 | 7.78 | 7.85 |
| CaO | 1.49 | 2.89 | 5.28 | 4.28 | 3.29 | 2.59 | 5.16 | 2.03 | 4.69 | 0.44 | 5.58 | 4.01 | 12.35 |
| Na2O | 5.99 | 4.56 | 5.60 | 4.87 | 6.33 | 4.11 | 4.01 | 5.59 | 5.47 | 2.34 | 5.65 | 1.40 | 0.10 |
| K2O | 2.51 | 1.94 | 1.29 | 4.17 | 2.93 | 6.34 | 5.49 | 4.20 | 3.97 | 8.47 | 2.28 | 6.92 | 5.23 |
| P2O5 | 0.40 | 0.03 | 0.28 | 0.30 | 0.16 | 0.52 | 0.14 | 0.00 | 0.51 | 0.06 | 0.10 | 0.90 | 1.41 |
| BaO | 0.03 | 0.07 | 0.07 | 0.24 | 0.10 | 0.07 | 0.24 | 0.09 | 0.14 | 0.12 | 0.22 | 0.44 | 0.50 |
| SrO | 0.03 | 0.04 | 0.06 | 0.07 | 0.05 | 0.51 | 0.08 | 0.42 | 0.38 | 0.03 | 0.09 | 2.61 | 1.53 |
| LOI | 1.33 | 3.32 | 5.14 | 4.79 | 2.79 | 4.25 | 5.19 | 6.38 | 5.77 | 2.32 | 3.20 | 12.07 | 20.35 |
| Total | 98.85 | 97.50 | 97.90 | 98.43 | 99.12 | 101.75 | 100.30 | 96.96 | 96.44 | 98.40 | 100.72 | 95.42 | 97.17 |

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| F ppm | 2564 | 5428 | 8037 | 6538 | 3203 | 4261 | 8110 | 5629 | 3957 | 4053 | 5350 | 11525 | 2337 |
| Cl ppm | 125 | 104 | 83 | 79 | 94 | 76 | 62 | 150 | 104 | 129 | 114 | 88 | 117 |

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Traces ppm | 193 | 201 | 209 | 249 | 218 | 250 | 187 | 198 | 242 | 273 | 279 | 212 | 254 |
| Li | 11.5 | 19.6 | 19.4 | 18.6 | 40.1 | 24.2 | 91.7 | 135.0 | 20.8 | 30.3 | 41.1 | 206.8 | 8.7 |
| S | 36.4 | 219.0 | 169.0 | 472.0 | 128.9 | 943.0 | 352.8 | 1870.0 | 1030.0 | 68.1 | 489.7 | 3820.0 | 672.0 |
| V | 20.6 | 33.9 | 139.2 | 89.1 | 40.0 | 145.1 | 65.1 | 105.0 | 101.0 | 120.3 | 91.1 | 63.3 | 47.4 |
| Co | 3.4 | 3.4 | 12.6 | 8.2 | 2.9 | 12.2 | 5.4 | 8.2 | 15.4 | 1.6 | 1.7 | 12.5 | 14.0 |
| Cu | 32.9 | 9.7 | 2.2 | 8.5 | 1.4 | 16.3 | 3.6 | 10.4 | 21.9 | 4.4 | 7.4 | 16.8 | 27.3 |
| Zn | 123.3 | 113.5 | 129.0 | 181.0 | 248.7 | 227.9 | 208.5 | 1916.0 | 588.0 | 964.0 | 451.1 | 1543.0 | 2094.0 |
| Ga | 12.1 | 10.1 | 10.3 | 18.0 | 19.6 | 22.5 | 12.0 | 7.4 | 13.9 | 9.4 | 16.4 | 6.0 | 3.0 |
| Rb | 26.8 | 23.7 | 16.8 | 46.0 | 40.1 | 28.2 | 75.3 | 57.4 | 48.1 | 88.7 | 78.3 | 87.9 | 55.3 |
| Y | 28.1 | 10.1 | 28.6 | 23.3 | 25.4 | 36.9 | 11.8 | 7.1 | 25.6 | 10.0 | 8.9 | 21.5 | 20.0 |
| Zr | 57.2 | 100.4 | 58.3 | 159.7 | 151.3 | 83.9 | 80.3 | 129.5 | 150.0 | 182.0 | 70.0 | 134.3 | 162.4 |
| Nb | 18.2 | 58.8 | 56.3 | 161.6 | 71.0 | 86.4 | 152.0 | 233.3 | 96.5 | 185.4 | 211.2 | 139.6 | 409.9 |
| Mo | 1.1 | 0.7 | 0.7 | 4.2 | 11.0 | 3.0 | 6.7 | 8.3 | 16.2 | 9.3 | 17.1 | 102.0 | 32.2 |
| Hf | 0.2 | 1.3 | 1.2 | 2.4 | 1.8 | 2.5 | 1.7 | 3.5 | 3.3 | 3.2 | 2.6 | 2.6 | 0.9 |
| Ta | 0.2 | 0.2 | 0.1 | 0.5 | 0.3 | 0.4 | 0.2 | 0.3 | 0.3 | 0.2 | 0.3 | 0.2 | 1.2 |
| W | 0.1 | 0.4 | 0.5 | 2.2 | 0.4 | 1.3 | 1.0 | 0.5 | 0.8 | 0.7 | 0.7 | 1.6 | 0.8 |
| Pb | 3.8 | 4.5 | 7.2 | 11.2 | 5.9 | 6.4 | 3.3 | 309.5 | 9.8 | 5.3 | 6.5 | 17.3 | 14.9 |
| Th | 2.4 | 4.6 | 5.1 | 8.4 | 1.8 | 4.5 | 3.7 | 6.2 | 15.5 | 11.4 | 10.7 | 28.7 | 50.5 |
| U | 0.1 | 0.0 | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.8 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| REE ppm | 193 | 201 | 209 | 249 | 218 | 250 | 187 | 198 | 242 | 273 | 279 | 212 | 254 |
| La | 10.9 | 21.8 | 16.2 | 19.9 | 25.4 | 48.0 | 128.9 | 358.3 | 292.0 | 298.5 | 334.1 | 3565.4 | 1908.3 |
| Ce | 30.0 | 64.8 | 45.3 | 52.2 | 55.2 | 149.3 | 342.1 | 832.7 | 645.0 | 588.9 | 721.8 | 6550.7 | 3950.3 |
| Pr | 5.7 | 11.5 | 7.2 | 9.9 | 7.9 | 22.8 | 44.1 | 96.9 | 81.5 | 79.5 | 76.8 | 676.7 | 439.6 |
| Nd | 28.5 | 56.3 | 32.9 | 57.2 | 32.7 | 79.7 | 152.4 | 343.1 | 327.0 | 295.1 | 268.5 | 2313.3 | 1579.0 |
| Sm | 5.6 | 8.1 | 8.6 | 21.0 | 5.1 | 16.2 | 15.5 | 29.5 | 45.5 | 30.3 | 32.9 | 191.0 | 158.1 |
| Eu | 1.7 | 2.0 | 2.7 | 5.8 | 2.0 | 3.4 | 2.5 | 5.6 | 10.0 | 6.3 | 4.3 | 35.1 | 31.2 |
| Gd | 4.3 | 4.3 | 8.1 | 13.5 | 4.6 | 10.7 | 9.4 | 9.9 | 20.0 | 12.3 | 15.1 | 62.9 | 60.1 |
| Tb | 0.6 | 0.4 | 1.3 | 1.6 | 0.6 | 1.3 | 0.7 | 1.3 | 2.2 | 1.5 | 1.0 | 7.6 | 6.7 |
| Dy | 3.0 | 1.2 | 6.8 | 6.9 | 3.0 | 5.9 | 2.1 | 2.8 | 7.0 | 3.8 | 2.0 | 12.1 | 12.1 |
| Ho | 0.6 | 0.2 | 1.3 | 1.1 | 0.6 | 1.1 | 0.3 | 0.4 | 1.1 | 0.5 | 0.2 | 1.3 | 1.1 |
| Er | 1.7 | 0.6 | 3.3 | 2.5 | 1.6 | 3.0 | 1.1 | 0.7 | 2.7 | 1.0 | 1.0 | 1.9 | 1.7 |
| Tm | 0.2 | 0.1 | 0.4 | 0.3 | 0.2 | 0.4 | 0.1 | 0.1 | 0.4 | 0.1 | 0.1 | 0.1 | 0.1 |
| Yb | 1.5 | 0.5 | 2.8 | 1.9 | 1.4 | 2.3 | 0.6 | 0.5 | 2.3 | 0.8 | 0.3 | 1.0 | 1.1 |
| Lu | 0.2 | 0.1 | 0.4 | 0.3 | 0.2 | 0.4 | 0.1 | 0.1 | 0.3 | 0.1 | 0.1 | 0.1 | 0.1 |

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