

APPENDIX I: FULL DATA AND ANALYTICAL TECHNIQUES - BAKER ET AL.
(1998) "METASOMATISM OF THE SHALLOW MANTLE BENEATH YEMEN BY
THE AFAR PLUME - IMPLICATIONS FOR MANTLE PLUMES, FLOOD
VOLCANISM, AND INTRAPLATE VOLCANISM

Table A1 lists trace element data determined by a variety of analytical techniques for the southern Yemen and Red Sea mantle xenoliths, along with major element data for representative mineral phases from these rocks. Table A2 lists Sr, Nd, and Pb isotope ratios for mineral separates from the xenoliths and Rb, Sr, Sm, Nd, U, and Pb trace element data determined by thermal ionisation mass spectrometric isotope dilution analysis.

MAJOR ELEMENT DATA

The small number of mineral major element analyses included as a footnote to Table A1 were made using a JEOL Superprobe 733 electron microprobe at University College, University of London. Analyses were performed at an accelerating potential of 15 kV, using a Link analyser and ZAF corrections. Analytical errors are better than $\pm 1\%$ for major elements and $\pm 10\%$ for minor elements.

TRACE ELEMENT DATA

Trace element data were determined by one or more of four techniques:

- (a) *Isotope dilution inductively-coupled plasma mass spectrometric (ID ICP-MS) analysis:* Trace element analyses were determined on acid-leached bulk mineral separates, taken into solution by attack with HF/HNO₃ and sequential evaporation with HNO₃, HCl and HNO₃, before final dissolution in 10% HNO₃. The solution was spiked with mixed Zr-Ba and U-Pb spikes: following measurement of isotopic ratios at the NERC ICP-MS facility, concentrations of Zr, Ba, U and Pb were determined by isotope dilution (ca. 4% error; 2 sd).

Concentrations of Rb, Sr, Y, Nb and Th (5-8% error; 2 sd) were determined by ratio to Zr or U, with mass bias calibrated by international standards.

(b) *Ion microprobe (SIMS) analysis:* SIMS analyses were performed with a Cameca IMS 4f ion microprobe at the University of Edinburgh, using a 8 nA primary beam of O⁺ and a beam size of 0-25 µm. Fuller details of the analytical technique are described by Chazot et al. (1996). Precision and accuracy (2 sd) of the ion microprobe data are better than ± 15% for Hf, ± 15% for Nb and Ba in the trace-element-depleted clinopyroxenes, and ± 10% for all other elements.

(c) *Inductively-coupled plasma mass spectrometric (ICP-MS) analysis:* ICP-MS analyses on a small number of samples were made on *unleached* mineral separates at the NERC ICP-MS facility.

(d) *Thermal ionisation mass spectrometric isotope dilution (TIMS ID) analysis:* TIMS ID analyses for the REE, Rb, Sr, U and Pb were carried out at the Royal Holloway University of London Radiogenic Isotope Laboratory (UK). Acid-leached mineral separates were taken into solution by standard acid-digestion techniques (HF/HNO₃ followed by sequential evaporation of HNO₃, HCl and HNO₃) and the resulting solution quantitatively split into fractions for TIMS ID analysis and Sr-Nd-Pb isotopic analysis. The TIMS ID fraction was spiked with a mixed REE spike, a mixed U-Pb spike and mixed Rb-Sr spike. U-Pb-Rb-Sr-REE were progressively separated using standard anion (REE-U-Pb) and cation (Rb-Sr) exchange techniques. Reproducibility of ID analyses are better than ± 0.5%.

Blanks for ID and isotopic analyses were typically less than Rb, 0.5 ng; Sr, 1.0 ng; REE La, 230 pg, Ce, 430 pg, Nd, 170 pg, Sm, 20 pg, Eu, 4 pg, Dy, 20 pg, Er, 12 pg, Yb, 12 pg; U, 0.5 ng; Pb, 0.5 ng. These blanks are negligible with the exception of Rb in samples JK4, JK10, BA8, and KA clinopyroxene, and U and Pb in the extremely trace-element-depleted samples (BA8 and KA), and trace element concentrations for all these samples were blank-corrected.

In many cases, trace element analyses were determined on the same samples using multiple techniques. Trace element concentrations determined using the

different techniques often exhibit considerable variation for individual elements, in particular: (i) low abundance elements in the depleted clinopyroxenes (e.g., Rb, Ba, Pb, Nb); (ii) differences observed between *in situ* analyses and analyses of bulk mineral separates where the bulk mineral separates can clearly contain trace element rich inclusions or contaminants (e.g., note the high Ba content of JK8 clinopyroxene determined by ID ICP-MS compared with the SIMS value); (iii) differences between leached (ID ICP-MS and TIMS ID) and unleached analyses (ICP-MS) of mineral separates (leached mineral separates almost without exception have higher trace element abundances); (iv) relatively high Pb contents determined by ICP-MS, even in incompatible trace element depleted minerals which relate to Pb blank levels of the ICP-MS technique. However, regardless of the analytical technique used, the trace element data clearly define the trace element differences between the minerals from the hydrous Ataq, anhydrous Ataq, and the anhydrous Bir Ali and Kod Ali xenoliths, discussed by Baker et al.

Sr, Nd, and Pb ISOTOPIC DATA

Sr, Nd, and Pb isotopic analyses were made on hand-picked, acid-leached mineral separates as described previously. Details of the mass spectrometry are described in Thirlwall (1991a and b). Blank-corrections were only necessary for the Pb isotopic analyses of samples BA8 and KA, but are generally small compared with the large difference in Pb isotopic composition these samples have compared to the Ataq mineral separates. Reproducibility of isotope ratios monitored by multiple analysis of standards are better than $^{87}\text{Sr}/^{86}\text{Sr}$, ± 0.00002 ; $^{143}\text{Nd}/^{144}\text{Nd}$, ± 0.000012 ; $^{206}\text{Pb}/^{204}\text{Pb}$, ± 0.010 ; $^{207}\text{Pb}/^{204}\text{Pb}$, ± 0.012 ; $^{208}\text{Pb}/^{204}\text{Pb}$, ± 0.028 .

REFERENCES CITED

- Chazot, G., Menzies, M. A., and Harte, B., 1996, Determination of partition coefficients between apatite, clinopyroxene, amphibole, and melt in natural spinel lherzolites from Yemen: Implications for wet melting of the lithospheric mantle: *Geochimica et Cosmochimica Acta*, v. 3, p. 423-437.
- Thirlwall, M. F., 1991a, Long-term reproducibility of multicollector Sr and Nd isotope ratio analyses: *Chemical Geology (Isotope Geoscience Section)*, v. 94, p. 85-104.
- Thirlwall, M. F., 1991b, High precision multicollector isotopic analyses of low levels of Nd as oxide: *Chemical Geology (Isotope Geoscience Section)*, v. 94, p. 13-22.

TABLE A1. TRACE ELEMENT DATA FOR REPRESENTATIVE MINERALS SEPARATED FROM SOUTHERN YEMEN AND RED SEA MANTLE XENOLITHS.

Sample	Rb	Ba	Sr	U	Th	Pb	Zr	Nb	Hf	La	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb	Y
JK2 cpx	1. 2.10	4.55	-	-	1.71	-	9.41	0.156	-	-	-	-	-	-	-	-	-	8.03	
2. 1.22	0.26	607	-	-	1.21	-	5.12	0.21	0.083	30.2	73.5	33.8	4.76	1.58	3.58	2.04	0.964	0.747	6.42
4. -	-	-	0.310	-	1.88	-	-	-	20.9	56.4	26.3	3.74	1.36	2.15	1.45	0.672	0.628	-	
JK8 cpx	1. 1.01	25.3	1135	-	1.37	-	7.82	1.71	-	-	-	-	-	-	-	-	-	40.9	
2. -	0.60	1070	-	-	0.83	-	2.84	0.60	-	-	-	-	-	-	-	-	-	32.3	
3. -	-	-	-	-	2.77	-	-	-	-	-	-	-	-	-	-	-	-	-	
JK8 am	1. 14.0	530	-	-	1.30	-	5.05	26.8	-	-	-	-	-	-	-	-	-	33.6	
2. 6.93	501	1030	-	-	0.97	-	5.06	22.8	-	2.16	29.9	90.1	68.7	15.4	4.90	14.8	9.91	2.94	
4. -	-	-	0.336	-	2.87	-	-	-	-	-	-	-	-	-	-	-	-	26.4	
JK8 ap	1. 0.89	-	-	-	-	-	0.94	1.43	-	-	-	-	-	-	-	-	-	-	
2. -	1160	33400	-	-	293	-	127	0.382	-	5.13	3770	6110	2180	342	91.0	194	72.0	20.0	
4. -	-	-	103.4	-	-	-	54.9	-	-	-	3913	6820	2313	317	82.4	197	84.9	21.7	
JK1 cpx	2. 0.25	35.3	-	-	0.59	-	21.2	2.49	0.62	4.20	6.77	2.63	0.82	0.315	1.82	1.83	1.32	1.62	
3. 0.79	-	64.4	-	-	0.59	-	1.68	18.8	0.68	-	4.79	10.8	3.04	1.22	0.46	1.63	1.94	9.77	
4. 0.535	-	67.6	0.125	-	-	0.241	-	-	-	4.93	11.5	4.63	0.966	0.378	1.25	1.81	1.21	1.11	
JK4 cpx	2. -	0.036	45.9	-	0.18	-	5.52	0.068	0.112	-	1.38	2.20	0.964	0.297	0.170	0.496	0.916	1.00	
3. 0.38	-	64.4	-	-	0.59	-	1.29	5.42	0.30	-	1.30	1.95	1.15	0.51	0.15	0.70	1.10	0.84	
4. 0.036	-	-	74.2	0.129	-	0.323	-	-	-	0.969	1.59	0.709	0.203	0.074	0.388	0.810	0.652	0.708	
JK10 cpx	4. 0.141	-	224.4	0.596	-	2.557	-	-	-	-	8.25	7.35	0.530	2.13	0.170	0.665	1.00	0.734	0.778
BA8 cpx	1. 0.055	0.33	25.1	-	0.39	-	21.9	0.092	-	-	-	-	-	-	-	-	-	17.6	
2. -	0.25	16.3	-	-	-	-	33.8	0.101	1.15	-	0.776	2.83	3.79	1.67	0.708	2.58	3.10	-	
3. 0.29	-	20.3	-	-	0.32	-	0.45	23.0	0.14	-	2.64	6.40	5.13	2.16	0.83	2.84	3.70	2.67	
4. -	-	0.090	-	-	0.042	-	-	-	-	1.77	4.33	3.38	1.26	0.531	1.92	2.80	1.78	1.61	
KA cpx	4. 0.011	-	69.9	-	-	0.081	-	-	-	0.150	1.27	2.86	1.42	0.614	2.32	3.45	2.27	2.09	

Note: cpx = clinopyroxene; am = amphibole; ap = apatite; 1. ID CP-MS data; 2. SIMS data; 3. ICP-MS data; 4. TIMS ID data

JK2 cpx: SiO₂ = 54.1; TiO₂ = 0.05; Al₂O₃ = 2.72; FeO = 2.46; MnO = 0.07; NiO = 0.08; Cr₂O₃ = 1.61; CaO = 20.4; MgO = 16.1; Na₂O = 1.59 wt% (n=22; Total = 99.2 wt%).

JK1 cpx: SiO₂ = 54.9; TiO₂ = 0.04; Al₂O₃ = 2.61; FeO = 2.38; MnO = 0.12; NiO = 0.08; Cr₂O₃ = 1.51; CaO = 19.7; MgO = 15.9; Na₂O = 2.08 wt% (n=6; Total = 100.3 wt%).

JK8 am: SiO₂ = 46.4; TiO₂ = 0.17; Al₂O₃ = 10.6; FeO = 3.22; MnO = 0.06; NiO = 0.17; Cr₂O₃ = 3.30; CaO = 9.71; MgO = 18.5; Na₂O = 3.99; K₂O = 0.67; Cl = 0.15 wt% (n=9; Total = 96.9 wt%).

JK8 ap: SiO₂ = 0.90; FeO = 0.40; CaO = 51.0; MgO = 0.31; Na₂O = 0.83; K₂O = 42.9; Cl = 2.37 wt% (n=1; Total = 98.8 wt%).

JK1 ap: SiO₂ = 52.8; TiO₂ = 0.30; Al₂O₃ = 4.42; FeO = 2.87; MnO = 0.11; NiO = 0.10; Cr₂O₃ = 1.51; CaO = 17.2; MgO = 16.0 wt% (n=1; Total = 99.6 wt%).

BA8 cpx: SiO₂ = 50.9; TiO₂ = 1.15; Al₂O₃ = 5.48; FeO = 3.13; MnO = 0.10; NiO = 0.17; Cr₂O₃ = 1.54; CaO = 16.5; MgO = 18.9; Na₂O = 1.03 wt% (n=3; Total = 98.9 wt%).

TABLE A2. RB-SR, SM-ND AND U-Pb ISOTOPIC AND TRACE ELEMENT DATA FOR MINERALS SEPARATED FROM SOUTHERN YEMEN AND RED SEA MANTLE XENOLITHS.

Sample number	Mineral phase	Rb (ppm)	Sr (ppm)	$^{87}\text{Sr}/^{86}\text{Sr}$	S _m (ppm)	Nd (ppm)	$^{143}\text{Nd}/^{144}\text{Nd}$	U (ppm)	Pb (ppm)	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
<i>Hydrous amphibole ± apatite-bearing peridotites from Ataq (south-western Yemen):</i>												
AT2	cpx	-	0.70364	-	-	0.512949	-	-	-	-	-	-
AT3	cpx	-	0.70343	-	-	0.512905	-	-	-	-	-	-
AT15	cpx	-	0.70344	-	-	0.512898	-	-	-	-	-	-
JK2	amph melt	-	0.70344	-	-	0.512898	-	-	-	-	-	-
	matrix cpx	-	0.70356	-	-	0.512902	-	-	-	-	-	-
	vein cpx	-	0.70355	3.741	26.25	0.512902	0.310	1.88	18.887	15.571	38.834	38.834
	opx	-	0.70356	3.178	24.05	0.512912	0.305	1.92	18.723	15.570	38.657	38.657
JK3	amph	-	0.70360	-	-	0.512897	-	-	-	-	-	-
JK7	cpx	-	0.70347	-	-	0.512937	-	-	-	-	-	-
JK8	cpx	-	0.70352	-	-	0.512927	-	-	-	-	-	-
	amph	-	0.70351	-	-	0.512921	-	-	-	-	-	-
	ap	-	0.70354	12.62	53.29	0.512882	0.336	2.87	18.951	15.587	38.945	38.950
<i>Anhydrous peridotites from Ataq (south-western Yemen):</i>												
JK1	cpx	0.535	67.60	0.70401	0.9660	4.627	0.512553	0.125	0.241	18.326	15.415	38.410
	repeat	-	-	0.70397	-	-	0.512552	-	-	-	-	-
JK4	cpx	0.036	74.19	0.70335	0.2031	0.7091	0.512898	-	-	-	-	-
	repeat	-	-	0.70329	-	-	0.51289	-	-	-	-	-
JK10	cpx	0.141	224.4	0.70355	0.5300	2.126	0.512982	0.596	2.557	18.853	15.567	38.827
	repeat	-	-	0.70349	-	-	0.512972	-	-	-	-	-
<i>Anhydrous peridotites from Bir Ali (south-western Yemen):</i>												
BA8	cpx	-	0.70291	1.257	3.379	0.513145	0.090	0.0422	17.887	15.499	37.749	37.749
<i>Pyroxenite from Bir Ali (south-western Yemen):</i>												
BA4	cpx	-	0.70344	-	-	0.513115	-	-	-	-	-	-
<i>Anhydrous peridotites from Kad Ali island (southern Red Sea):</i>												
KA	cpx	0.011	69.9	0.70219	1.422	2.859	0.513519	-	0.0807	18.183	15.492	37.795
	repeat	-	-	0.70216	-	-	0.513512	-	-	0.1207	18.274	15.616
K117	cpx	-	-	0.70306	-	-	0.512968	-	-	-	-	-

Note: All trace element data in this Table was determined by thermal ionisation mass spectrometric isotope dilution analysis.