THE COMPOSITION OF THE PRIMITIVE UPPER EARTH'S MANTLE.

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The primitive mantle contains the silicate portion of the Earth after core and before crust formation. The upper convecting mantle is probably separated from the lower mantle convection by a density barrier observable in a seismic discontinuity at about 670 km depth. Ringwood and Irifune (1988) assume that the transformation of the Mg_2SiO_4 spinel into a perovskite structure of $MgSiO_3$ (plus MgO) in harzburgite-like rocks is responsible for this discontinuity. The upper mantle has a mass of 1.07 x 10^{21}t (about 25 % of the bulk mantle) and the crust represents a mass of 0.03 x 10^{21} t.

Several approaches have been used by different authors to constrain the composition of the primitive mantle. They were mainly based on comparison with primitive chondritic matter (for refractory elements), extrapolations from depleted to fertile peridotite and komatiite compositions, element correlations in primitive and fractionated rock species such as oceanic basalts, global heat flow balances and radioactive/ radiogenic isotope transport between major units of the Earth. The largest sets of primitive mantle values were published by Jagoutz et al. (1979) and by Hofmann (1988). We will use these data as reference for our evaluation (Column E of Table 1).

Our two approaches to get additional information on primitive mantle concentrations of about 40 elements are related to a detailed investigation of the two spinel lherzolite containing tectonites of Balmuccia and Baldissero in the Ivrea-Verbano Complex of northern Italy. These rocks are very fresh and probably represent typical materials of the moderately depleted sub-lithospheric mantle which convects and produces MORB-type melts. We have analyzed 32 large samples by various instrumental methods (RFA, ICP, AAS, INA etc.) (Hartmann and Wedepohl, 1991). Both peridotite masses contain mainly lherzolite with an average modal composition of 56 % olivine, 28 % orthopyroxen, 14 % clinopyroxene and 1.5 % spinel. They have lost on average 6 % MORB by earlier partial melting. The heterogeneity inside the two masses can be characterized by the variation of Al_2O_3 from 2.0 to 5.0 %.

In our first approach we have used the correlations of the elements Li, Na, Sc, Ti, V, Ga, Sr, Y, Zr, Nb, REE, Hf, Ta to the Al_2O_3-content of the samples which partly reflects the crystal chemical behavior of these elements in the clinopyroxene structure. The lines of regression in these correlations can be used to define the element concentrations at 4.0 % Al_2O_3 which is the Al concentration of the primitive mantle reported by Hofmann (1988) and other authors. These interpolated primitive mantle values are listed in Column C of Table 1 beside concentrations of 94 % of the Balmuccia average plus 6 % MORB (the latter values are from Hofmann, 1988 and Wedepohl, 1981).

For our second model we have calculated primitive mantle compositions from the sum of 97.2 % Balmuccia mantle plus 2.8 % bulk crust concentrations of the various elements. The bulk crust consists of about 75 % continental and 25 % oceanic crust. The composition of the continental crust has recently been estimated by the present author on the

basis of large data sets of upper crustal rocks as well as granulites and petrologic information on crustal layering. It is less mafic and has higher concentrations of highly incompatible elements (including heat producing isotopes) than the estimate by Taylor and McLennan (1985). The difference between the two crustal estimates which are listed in Column D of Table 1, has only influence on "primitive mantle" values of the highly incompatible elements K, Rb, Ba, Pb, U and LREE.

The balance based on our data indicates that the crust consists of almost half of all partial melting products of the convecting upper mantle. The continental part of the crust has on average a tonalitic composition and the oceanic part represents MORB. The other more refractory half of the partial melting products was either retained in the mantle or returned into it during Earth's history. The composition of the moderately depleted upper mantle (including the highly depleted lithospheric part) is in balance with the composition of the crust with the exception of the elements U (Th,Cs), Rb, Pb, K (and Tl). The primitive mantle has contained these elements in unidentified K-rich minerals which have not survived. A part of the crustal content of these elements was probably supplied from the lower mantle. Both of our models confirm that the average spinel lherzolite from Balmuccia is a perfect representative of the typical upper mantle composition. They also confirm that the upper mantle has its separate convecting system which does not allow major material exchange with the lower mantle. About 30 of our new "primitive mantle" values are close to those published by Jagoutz et al. (1979), Hart and Zindler (1986) and Hofmann (1988) on the basis of different methods. Discrepancies to be mentioned occur in case of (F,Na,P, S), Ti, Cr, Fe and Cu. Our differences in Na might be caused by the selection of the Balmuccia peridotite as model material. This point requires additional research. We claim that at least our "primitive mantle" values on F, P, S, Cr, Fe and Cu are superior to those in the reported literature.

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Table 1

Balances for calculation of primitive mantle concentrations based on moderately depleted mantle rocks from Ivrea (N. Italy)

	A Spinel lherzolite Balmuccia $\bar{x}_{18} \pm s$	B Spinel lherzolite Baldissero $\bar{x}_{14} \pm s$	C Primitive mantle values from element-Al relations/from 94 % Balmuccia + 6 % MORB	D Primitive mantle values from 97.2 % Balmuccia + 2.8 % bulk crust (Wedepohl, 1991/ Taylor, McLennan, 1985)	E Primitive mantle values Jagoutz et al. (1979) Hart and Zindler (1986) Hofmann (1988)
Li	2.4 ± 0.4	2.0	2.6 / 2.8	2.7 / 2.7	2.4 J
F	6 ± 2	5 ± 2	/ 15	19 /	13.5 J
Na	1187 ± 336	1329 ± 114	1610 / 2190	1770 / 1760	2460 H 2730 J
Mg	234600 ± 10300	239400 ± 4820	/ 223680	229060 / 229235	228000 H 225000 J
Al	16880 ± 4230	16300 ± 1320	/ 20840	18670 / 18750	21500 H 21700 J
Si	209400 ± 930	208500 ± 1400	/ 209600	210000 / 209680	214800 H 214000 J
P	39 ± 10	26 ± 12	/ 67	58 /	83 H & Z
S	232 ± 114	144 ± 27	/ 272	251 /	
K	23 ± 5	26 ± 4	/ 124	450 / 223	258 H 260 J
Ca	22300 ± 6070	19440 ± 1860	26800 / 25800	23110 / 23380	22940 H 26600 J
Sc	15.9 ± 3.1	14.4 ± 0.9	18.0 / 17.4	16.1 / 16.4	14.9 H 16 J
Ti	623 ± 273	498 ± 53	860 / 1006	743 / 768	1085 H 1300 J
V	83. ± 20	72 ± 5	100 / 93	85 / 87	83 J
Cr	2568 ± 176	2628 ± 38	/ 2440	2500 / 2500	3465 J
Mn	1053 ± 39	1046 ± 40	/ 1062	1048 / 1061	1000 J
Fe	64500 ± 4120	63400 ± 3650	/ 64850	64150 / 64670	58600 H 58700 J
Co	106 ± 3	100 ± 30	/ 102	104 / 104	100 J
Ni	2040 ± 117	2071 ± 72	/ 1930	1990 / 1990	2080 H 1950 J
Cu	35 ± 17	27 ± 5	/ 37	35 / 36	6.4 J
Zn	51 ± 3	50 ± 2	/ 53	51 / 52	59 J
Ga	3 ± 0.8	2.6 ± 0.4	3.7 / 3.8	3.4 / 3.4	3.9 J
Rb	(0.05)	(0.05)	/ 0.34	1.5 / 0.73	0.54 H 0.73 J
Sr	7.5 ± 3	6.1 ± 1	10.2 / 15.0	15.3 / 13.7	18.2 H 19.6 H & Z 25 J
Y	2.9 ± 1.1	2.7 ± 0.3	4.2 / 4.9	3.6 / 3.5	3.9 H 4.6 J
Zr	4.8 ± 1.6	3.9 ± 0.8	6.0 / 10.8	10.0 / 7.5	9.7 H 11 J
Nb	(0.5)		0.6 / 0.68	(0.88)/(0.74)	0.62 H 0.9 J
Ba	1.1 ± 0.7	<0.5	/ 3.9	17.9 / 6.7	6.0 H 6.9 J
La	0.12 ± 0.13	0.04 ± 0.02	0.20 / 0.35	0.76 / 0.48	0.61 H 0.70 J
Ce	0.40 ± 0.45	0.17 ± 0.10	0.80 / 1.1	1.4 / 1.2	1.6 H
Nd	0.45 ± 0.49	0.22 ± 0.07	0.75 / 1.1	1.1 / 0.85	1.19 H 1.17 H & Z
Sm	0.19 ± 0.16	0.13 ± 0.02	0.44 / 0.40	0.32 / 0.28	0.39 H 0.42 J
Eu	0.092 ± 0.065	0.064 ± 0.008	0.14 / 0.16	0.13 / 0.09	0.14 H 0.17 J
Gd	0.33 ± 0.21	0.26 ± 0.03	0.50 / 0.61	0.44 / 0.32	0.51 H
Tb	0.08 ± 0.04	0.06 ± 0.01	0.10 / 0.13	0.093 / 0.078	0.094 H
Dy	0.45 ± 0.22	0.39 ± 0.04	0.57 / 0.80	0.56 / 0.56	0.64 H
Yb	0.31 ± 0.12	0.30 ± 0.02	0.43 / 0.53	0.37 / 0.37	0.41 H 0.46 J
Lu	0.052 ± 0.021	0.051 ± 0.003	0.066 / 0.08	0.063 / 0.061	0.064 H 0.069 J
Hf	0.13 ± 0.04	0.10	0.20 / 0.30	0.26 / 0.21	0.27 H 0.34 J
Ta	0.03 ± 0.01	0.04 ± 0.01	0.035 / 0.041	0.050 / 0.051	0.035 H 0.03 J
Pb	(0.035)	(0.016)	/ (0.08)	(0.28)/ 0.20	0.18 H
U	(0.004)	(0.002)	/ (0.008)	(0.036)/ 0.023	0.020 H 0.026 J