PARTITIONING OF Ni, Co, Sc, La, AND OTHER ELEMENTS BETWEEN OLIVINE AND NATURAL BASALTIC MELT AT 75 KBARS AND 1800°C, AND IMPLICATIONS FOR THE EARLY THERMAL HISTORY OF THE EARTH;

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Introduction: Theories of the formation of the Earth strongly suggest that the Earth should have been substantially molten during and immediately after accretion (e.g., Wetherill, 1985). Experimental determinations of phase equilibria also lead to the expectation that the Earth was at least partially molten early in its history, producing a magma ocean (Takahashi, 1986). Estimates of the composition of the upper mantle indicate that many elements are present in chondritic ratios (e.g., Jagoutz *et al.*, 1979). In apparent contradiction to these considerations, experimental measurements of element partition coefficients show that segregation of Mg-perovskite and majorite garnet would fractionate the ratios of these elements away from chondritic values (Kato *et al.*, 1987, 1988a,b).

It has been known for some time that the Mg/Si ratio inferred by most authors for the upper mantle of the Earth is higher than in the chondritic meteorites (e.g., Jagoutz *et al.*, 1979). The class of primitive meteorites most similar to the upper mantle is the C3V carbonaceous chondrites. These meteorites are not good candidates for proto-Earth matter, however, as their Ir/Au ratio is almost twice as high as the CI ratio and estimates for the Earth's upper mantle (Kallemeyn and Wasson, 1981). Recently Agee and Walker (1988) have offered an innovative proposal to produce such a high ratio from initially chondritic material. The basis of their proposal is a careful experimental study which shows that olivine becomes neutrally buoyant in a melt representative of upper mantle composition at about 80 kbars. This experimental observation has led them to propose that the high Mg/Si ratio in the upper mantle results from mixing into the upper mantle of up to 30% olivine after solidification of a terrestrial magma ocean. This olivine crystallized from a magma ocean which was initially continuous in depth and formed a neutrally bouyant septum dividing the molten outer part of the Earth into two separated oceans. The result is a homogeneous upper mantle with a Mg/Si ratio greater than found in any class of chondritic meteorite except, possibly, the C3V chondrites (Palme and Nickel, 1986).

This novel proposal may be tested against olivine/melt partition coefficients for elements present in the upper mantle in chondritic ratios (Drake, 1989). For example, Sc and La are present in chondritic ratios at chondritic abundance levels. Nickel and Co are present in chondritic ratios at about 20% of chondritic abundance levels. If the elements in each pair have sufficiently different partition coefficients, their chondritic ratios may be used to limit possible olivine addition into the upper mantle. This contribution focuses on the partitioning of Ni, Co, Sc, La, and other elements between olivine and natural basaltic melt.

Experimental and Analytical Procedures: Approximately 100 mg aliquots of ground KLB-1 (kindly provided by E. Takahashi) were doped with 1-2 wt. % each of Ni, Co, and Sc, and were loaded into graphite capsules. The capsules were placed inside a lanthanum chromite sleeve that serves as the furnace (the graphite also serves as a furnace until it transforms to diamond) which in turn was placed in a standard MgO octagon pressure medium. The entire assembly was inserted into a uniaxial-split sphere cubic anvil pressure apparatus (USSA-2000). Charges were compressed to 75 kbars and heated to 1800°C for approximately one hour. A temperature gradient of about 200°C exists from the cold to the hot end of each charge. Charges were quenched by turning off power to the lanthanum chromite furnace. Pressure was released gradually over a period of several hours. During the experiments, La and Cr from the furnace contaminated the charges.

Each charge was made into a polished thick section. Successful run products typically consist of a subsolidus assemblage of olivine, orthopyroxene, clinopyroxene, spinel, and probably garnet at the cold end, and silicate melt containing quench crystals of olivine at the hot end. The liquidus is marked by the appearance of non-quench textured olivine crystals. Analysis was by electron microprobe using standard techniques. All of the experiments run thus far are synthesis experiments. Until reversals have been conducted, formal demonstration of how closely these experiments approached equilibrium is not possible. Homogeneity of phase compositions in the same region of the charge may indicate an approach to local equilibrium.

Results: Typical analyses of olivine and adjacent melt are given in Table 1, together with olivine/melt partition coefficients. The melt also contains CO_2, accounting for the low totals. Olivine/melt partition coefficients (D) at 75 kbars and 1800°C, rounded to one significant figure are D(Ni) = 2, D(Co) = 1, D(Sc) = 0.1, and D(La) < 0.007. The value for Ni is identical to that estimated by Drake (1989) on the basis of extrapolation of trends from experiments conducted at lower temperatures and pressures. The value of unity for Co is higher than the value of 0.6 estimated by Drake (1989). The value for Sc is lower than the value of about 0.3 used by Drake (1989) and derived from experiments conducted at one bar in the 1100°C to 1250°C temperature range. Lanthanum is highly incompatible as expected.

Table 1. Analyses of four olivines and adjacent melt, and calculated partition coefficient values (D).

	MgO	SiO2	FeO	Al2O3	CaO	CoO	Cr2O3	NiO	Sc2O3	MnO	Na2O	La2O3	Total
olivine	52.17	41.03	5.00	0.19	0.12	0.63	0.42	0.25	0.11	0.07	0.04	<0.02	100.05
melt	29.34	42.93	7.89	4.41	3.24	0.60	1.28	0.13	1.26	0.14	0.43	3.89	95.54
D ol/m	**1.8**	**0.96**	**0.6**	**0.04**	**0.04**	**1.1**	**0.3**	**1.9**	**0.09**	**0.5**	**0.09**	**<0.005**	
olivine	52.86	40.99	4.98	0.20	0.11	0.62	0.36	0.29	0.12	0.07	0.04	<0.03	100.67
melt	29.51	42.87	7.82	4.52	3.34	0.63	1.31	0.13	1.24	0.15	0.46	4.10	96.08
D ol/m	**1.8**	**0.96**	**0.6**	**0.04**	**0.03**	**1.0**	**0.3**	**2.2**	**0.10**	**0.5**	**0.09**	**<0.007**	
olivine	53.05	41.82	4.84	0.21	0.14	0.63	0.40	0.22	0.11	0.06	0.05	<0.03	101.56
melt	30.75	43.95	7.84	4.44	3.21	0.66	1.21	0.15	1.18	0.12	0.45	3.51	97.47
D ol/m	**1.7**	**0.95**	**0.6**	**0.05**	**0.04**	**1.0**	**0.3**	**1.5**	**0.09**	**0.5**	**0.11**	**<0.009**	
olivine	52.88	41.10	4.81	0.16	0.13	0.59	0.43	0.26	0.11	0.07	0.04	<0.03	100.61
melt	30.27	43.43	7.81	4.49	3.23	0.63	1.25	0.16	1.23	0.12	0.46	4.10	97.18
D ol/m	**1.7**	**0.95**	**0.6**	**0.04**	**0.04**	**0.9**	**0.3**	**1.6**	**0.09**	**0.6**	**0.09**	**<0.007**	

Conclusions: The low value of D(Sc) = 0.1 indicates that chondritic Sc/REE ratios cannot be used to detect addition of olivine to the upper mantle. The Ni/Co ratio remains an indicator of olivine accumulation. The Ni/Co ratio is 20-25% higher than its initial value for a 30% addition of olivine to the upper mantle. The implication of these experiments and those of Kato *et al.* (1987, 1988a,b) is that the Earth did not undergo extensive fractionation during and immediately following accretion. One possibility is that the Earth did not become substantially molten. Alternatively, if the Earth was indeed substantially molten, then it is possible that minerals were entrained in magma and were unable to segregate (Tonks and Melosh, 1988). In the former case, the accretional process must have delivered gravitational potential energy more slowly than current theory predicts, and an origin of the Moon in a giant impact would be unlikely. In the latter case, the high Mg/Si ratio in the Earth relative to all classes of chondrites would be intrinsic to the Earth, implying that the accretional process did not mix material between 1 AU and 2-4 AU where most chondritic meteorites are presumed to originate.

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