# OLIVINE, BETA SPINEL AND MAJORITE/MELT PARTITIONING AND THE EARLY THERMAL HISTORY OF THE EARTH;

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**Introduction:** Theoretical considerations of planetary accretion suggest that terrestrial planets should begin to melt by the time they achieve about one tenth of an Earth mass [1]. Hypotheses for the origin of the Moon involving giant impacts suggest that the Earth would have been substantially melted or even vaporized as a result of the impact [2]. Recent high pressure experimental phase equilibrium studies [3,4] have shown a convergence of the liquidus and solidus for candidate upper mantle compositions, and may be interpreted in terms of a substantially molten Earth during and subsequent to accretion. It has also been proposed that the superchondritic Mg/Si ratio of 1.12 relative to CI in the upper mantle [5] is a consequence of flotation of olivine at high pressure in a buried magma ocean, with subsequent mixing of that olivine into the upper mantle [6]. Mixing of approximately 30% olivine is required.

The proposal that the early Earth was molten during and immediately subsequent to accretion may be tested against the approximately chondritic ratios of a variety of elements with different geochemical affinities in the upper mantle. Refractory lithophile elements such as Sc and La are present in the upper mantle of the Earth in chondritic ratios and absolute abundances, while the moderately siderophile elements Ni and Co are present in chondritic ratios at about 20% of chondritic abundances. If the elements in each pair have sufficiently different partition coefficients, their chondritic ratios may be used to limit possible mineral addition into the upper mantle [7].

**Procedures and Results:** We have investigated experimentally the partitioning of a number of elements among various phase pairs at high pressures. Aliquots of ground KLB-1 were doped with 1-2 wt. % each of Ni, Co, and Sc, loaded into a graphite or rhenium capsule, placed inside a lanthanum chromite furnace within a standard MgO octagon pressure medium, and inserted into a uniaxial-split sphere cubic anvil pressure apparatus (USSA-2000).

We have conducted experiments at 75 kbars and 1800°C for approximately one hour, and at 100 kbars and 2080°C and 165 kbars and 2260°C for 10 minutes. There is a temperature gradient of about 200°C across the charge. Homogeneity of phase compositions in the same region of the charge may indicate an approach to local equilibrium. The melt is unquenchable, and yields a dendritic texture with quench olivine crystals in glass. Partition coefficients between liquidus olivine and melt were determined at 75 kbars and 100 kbars, and between majorite and melt and beta-spinel and melt at 165 kbars. Results are given in Tables 1 and 2, where they are compared with results of other workers.

**Discussion:** The shaded region of Figure 1 exhibits the variation of the Ni/Co ratio which would be observed in the upper mantle of the Earth with the addition of olivine into the upper mantle [8]. Approximately 30% olivine addition to the upper mantle is necessary to explain the Mg/Si ratio currently observed assuming an initially CI chondritic value. The upper line corresponds to olivine crystallizing at 90% fraction of liquid remaining from a global magma ocean, and the lower line to 80% fraction of liquid remaining. The currently observed Ni/Co ratio for the upper mantle of the Earth is approximately 0.9 x CI. The conclusion drawn is that addition of 30% olivine to the upper mantle to raise the Mg/Si ratio from CI chondritic to its present value yields a Ni/Co ratio 20-25% higher than its initial value, contrary to observation. The low partition coefficient for Sc removes the Sc/REE ratio as a constraint on the olivine addition process.

The conclusion, drawn by [9,10], that *at most* minor amounts of majorite fractionation [11] during a global magma ocean phase are consistent with the chondritic ratios of refractory lithophile elements, is supported by our experimental results. This conclusion is in accord with that of [6] based on major element considerations.

The implication of these experiments and those of [9,10,12] 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. If so, 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. Alternatively, if the Earth was indeed substantially molten, then it is possible that vigorous convection suppressed segregation of minerals from magma [13]. In either case, the high Mg/Si ratio in the Earth relative to most classes of chondrites would be intrinsic to the Earth, implying that the accretional process did not mix material efficiently between 1 AU and 2-4 AU where most chondritic meteorites are presumed to originate.

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TABLE 1. Olivine/melt (Ol/l) partition coefficients and beta spinel/melt (ß/l) partition coefficients * = not detected or not measured.

| | Ol/l a | Ol/l b | Ol/l c | ß/l d |
|---|---|---|---|---|
| Na | 0.09 | 0.2 | 0.13 | * |
| Mg | 1.8 | 1.5 | * | 1.2 |
| Al | 0.04 | 0.07 | 0.05 | 0.3 |
| Si | 1.0 | 1.0 | * | 0.9 |
| P | * | 0.1 | * | * |
| Ca | 0.04 | 0.05 | 0.02 | 0.5 |
| Sc | 0.1 | 0.1 | * | 0.2 |
| Cr | 0.3 | 0.3 | 0.26 | 0.8 |
| Mn | 0.5 | * | 0.42 | 1 |
| Fe | 0.6 | 0.5 | 0.59 | 1.5 |
| Co | 1 | 0.8 | * | 2 |
| Ni | 2 | 1 | 0.94 | 2 |
| Ga | * | 0.05 | * | 0.6 |
| Ge | * | 0.3 | * | 1.2 |
| Mo | * | * | * | 1.5 |
| La | <0.007 | * | * | * |

a This work 75 kbar; 1800°C
b This work 100 kbar; 2080°C
c Ohtani *et al.* [14] 160 kbar; 1950°C
d This work 165 kbar; 2260°C

TABLE 2. Majorite/Melt Partition Coefficients. * = not measured

| | 1 | 2 | 3 |
|---|---|---|---|
| Mg | 0.9 | * | * |
| Al | 2.5 | 2.5 | 3.06 |
| Si | 1.1 | * | * |
| P | 1.0 | * | * |
| Ca | 0.6 | 0.6 | 0.47 |
| Sc | 1.5 | 1.7 | 1.64 |
| Cr | 1.5 | * | 2.33 |
| Mn | 0.7 | * | 0.6 |
| Fe | 0.3 | 0.6 | 0.42 |
| Co | 0.3 | * | * |
| Ni | 0.2 | * | 0.15 |
| Ga | 0.8 | * | * |
| Ge | 1 | * | * |
| Zr | 2 | 0.6 | 0.46 |

1 This work 165 kbar; 2260°C
2 Kato *et al.* 1988 [10] ~160 kbar; ~2100°C
3 Ohtani *et al.* 1989 [14] 160 kbar; 1950°C

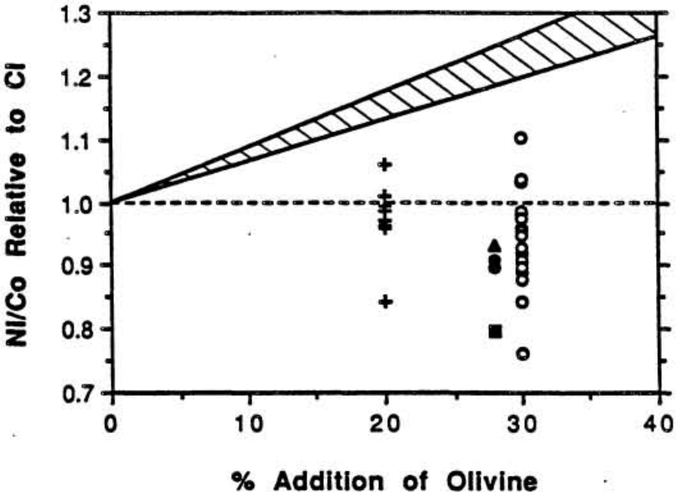


Figure 1. The shaded envelope exhibits the variation of the Ni/Co ratio which would be observed in the upper mantle of the Earth with the addition of olivine into the upper mantle [8]. Open circles at 30% olivine addition show the Ni/Co ratio of 26 mantle nodules (20 from [15]; 6 from [16]). Closed circles, arbitrarily plotted at 28% olivine addition for clarity, represent the most primitive of the mantle nodules of [16]; the closed triangle is an average of the 6 mantle nodule Ni/Co values [16]; the closed square is the Ni/Co ratio of the theoretical upper mantle composition pyrolite (from [16]). The 8 crosses are arbitrarily plotted at 20% olivine addition to illustrate the variation of the Ni/Co ratio among the undifferentiated meteorite types CI, CM, CO, CV, H, L, LL, EH, and EL. All Ni/Co ratios are normalized to CI chondrites [17]).

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