THE FEO, NIO AND COO CONTENTS OF SOLAR SYSTEM BASALTS AND THEIR SIGNIFICANCE FOR CORE FORMATION IN PLANETARY BODIES.

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Introduction: In Table 1 we have compiled the chemical compositions, including Ni and Co, of representative basalts from Earth, Moon, Mars and Vesta. The SiO_2 and MgO concentrations of all basalts cover only a small compositional range, suggesting a similar extent of fractionation. The Ni and Co contents increase with the radius of the planet, with very low concentrations in Vesta and increasing through Moon and Mars to the high concentrations in the terrestrial basalts. The concentrations of FeO, CoO and NiO in solar system basalts reflect the combined effect of two processes, early metal-silicate equilibration during core formation and fractionation during basalt formation. Metal-silicate fractionation depends on pressure, temperature and oxygen fugacity. The effect of oxygen fugacity can be eliminated by normalizing Co and Ni to Fe, as all three elements have exactly the same dependence on oxygen fugacity [1]. Lunar and Vesta basalts (eucrites) have about twice the FeO content of terrestrial and Venusian basalts (not shown in Table 1), which must have formed at more reducing conditions.

Table 1: Composition of solar system basalts

		Earth MORB	Moon low-Ti, 15495	Mars Shergotty	Vesta Juvinas
radius	[km]	6378	1745	3397	258
est. p	[GPa]	136	max 5	max 23	max 0.2
SiO_2	wt %	50.45	48.98	51.34	49.14
MgO	wt %	7.58	9.66	9.25	7.00
Al_2O_3	wt %	15.26	9.28	6.88	13.04
CaO	wt %	11.30	10.44	9.60	10.73
FeO	wt %	10.43	19.30	19.42	17.88
Ni	ppm	150	47	79	4.0
Co	ppm	50	45	40	4.7
Ni/Co		3.00	1.04	1.98	0.85
Ni and Co concentration in planetary mantles					
Ni	ppm	1860 [2]	470 [3]	400 [4]	38 [5]
Co	ppm	102 [2]	90 [3]	68 [4]	13 [5]
Ni/Co		18.7	5.2	5.9	2.9

Tab. 1: Size, estimated pressure at core-mantle boundary (est. p) and chemical composition of typical basalts and mantle of Earth, Moon, Mars and Vesta.

The one bar metal-silicate partition coefficients increase in the sequence Fe, Co Ni. If, as is assumed here, all planets had initially chondritic ratios of these three elements, the chondrite normalized contents of FeO, CoO and NiO in planetary mantles should decrease in this sequence. Subsequent basalt formation will exacerbate this effect, as the olivine/melt partition coefficients increase in the same sequence (FeO, CoO, NiO). Olivine is the major mineral in the residue of partially molten silicates, in addition basalts may have fractionated olivine on cooling. Therefore, the FeO, CoO and NiO contents of planetary basalts are absolute lower limits to the corresponding mantle concentrations.

Constraints on Ni and Co in silicate melts by 1 atmosphere experiments. The metal-silicate partition coefficients of Co and Ni are well known at pressures of about one atmosphere. Recent experimental results on Ni and Co partitioning between metal and silicate with eucritic melts were used to model partial melting and fractional crystallization processes on the eucrite parent body. This leads to concentrations of about 9.5 ppm Ni and 7 ppm Co at 1190°C and about 38 ppm Ni and 15 ppm Co at 1600°C in eucrites [6]. These results are directly applicable to metal-silicate partitioning with more mafic melts, as the activities of FeO, CoO and NiO are independent of the composition, within the range of geologically reasonable compositions [1]. Thus the one atmosphere pressure data define the range of Ni and Co contents that can be produced in the mantles of small planetesimals. The observed low concentrations of Ni and Co in eucrites are at the lower end of calculated silicate compositions, supporting that eucrites are partial melts from a chondrite source region [7], at least with regard to Ni and Co.

A comparison of these results with basalts from Moon, Mars and Earth shows that their Ni and Co contents are in all cases above those predicted by the application of the one bar partition coefficients to melting models. The difference is even larger considering that the silicate mantles of Moon, Mars and Earth are higher in Ni and Co than the corresponding partial melts. The Earth's mantle has 1860 ppm Ni and 102 ppm Co [2], the Ni content of the lunar mantle is estimated to 470 ppm and 90 ppm Co by Delano [3]. Martian mantle estimates are in the range of those of the lunar mantle (400 ppm Ni and 70 ppm Co [4]).

Effect of pressure: It is thus clear that the Ni and Co contents in the silicates of the three planets Moon, Mars and Earth cannot be explained by low pressure equilibration between metal and silicate.

Li and Agee [8] measured the decrease of Ni and

Co metal-silicate partition coefficients with increasing pressure. Extrapolation of their high pressure data to low pressures lead to much lower partition coefficients than measured at one atmosphere (Fig. 1). In addition their pressure dependence is relatively weak and has little effect when applied to the interior of the Moon (max 5 GPa) and Mars (max 23 GPa).

We have recently reported new metal-silicate partition coefficients for Ni and Co (Fig. 1) [9] which take into account the high partition coefficients at one atmosphere and show a strong decrease between 1 atm and 5 GPa and a much flatter decrease at higher pressures. It is clear from Fig. 1 that the decrease of metal-silicate partition coefficients with increasing pressure cannot be described with a single parameter, as, for example done by [10].

Moon: When applied to the Moon, metal-silicate partition coefficients would increase by a factor of four at a pressure of 4 to 5 GPa, allowing about 150 ppm Ni and 50 ppm Co in the silicate portion of the Moon, assuming chondritic Fe/Ni in the core. This could explain the Ni and Co contents of low Ti-mare basalts but the calculated Ni and Co contents are too low for those estimated for the lunar mantle (Ni = 470 and Co = 90 ppm, Table 1). Alternate scenarios for the Moon involve a high Ni-core. It is also possible that the lunar mantle acquired its Ni and Co contents from the mantle of the impactor where metal-silicate equilibration could have occurred at significantly higher pressures, leading to higher Ni and Co in the mantle.

Mars: The possible Ni and Co contents for the Martian mantle are somewhat above those of the lunar mantle as the increase of the partition coefficients with pressure becomes less steep at higher pressures (Fig. 1). The difference in Ni and Co partition coefficients between 15 and 20 GPa are about 40 %. Estimates for the Martian mantle are similar to those for the lunar mantle. This and the somewhat higher pressure for core-mantle equilibrium will allow to establish the observed Ni and Co concentrations by metal-silicate equilibration at the bottom of a Martian magma ocean.

Earth: Equilibration of core forming metal with a terrestrial magma ocean at a depth of some 900 km has been postulated based on high pressure metal-silicate partition coefficients for Ni and Co (summarized in [10]). Recent data have, however, shown that the approximately chondritic Ni/Co ratio of the Earth's mantle cannot be produced by high pressure metal-silicate equilibration [11]&[9]], Fig.1). Other, non-equilibrium models are required to explain this (e.g. inefficient core formation [12]; heterogeneous accretion models ([13], [14], [15]) or the most recent model of [16]).

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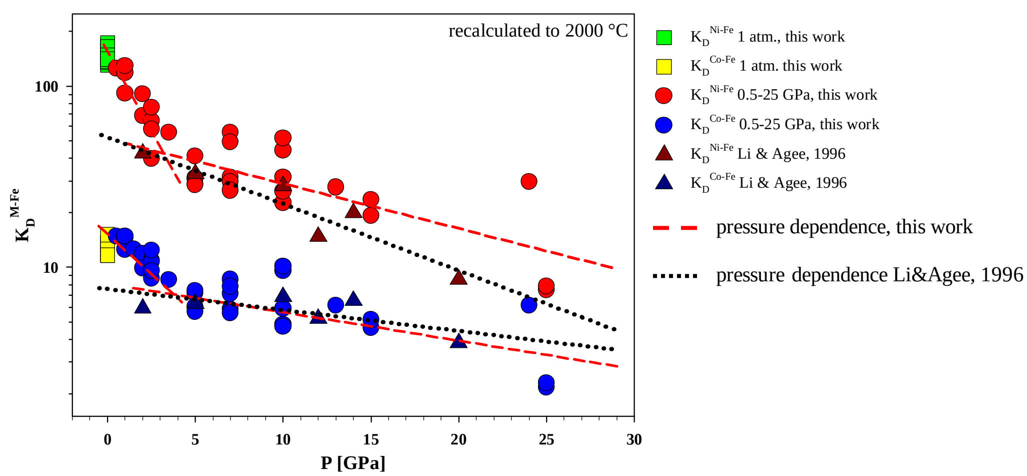

Fig. 1: Pressure dependences of $K_D^{Ni\text{-}Fe}$ and $K_D^{Co\text{-}Fe}$. The red dashed line is the pressure dependence of this work, the black dotted line is the pressure dependence described by Li & Agee [8].