

**SEGREGATION OF EARTH'S CORE IN AN HADEAN MAGMA OCEAN.** M. J. Walter, Institute for Study of the Earth's Interior, Okayama University, Misasa, Tottori-ken 682-0193, Japan (walter@misasa.okayama-u.ac.jp).

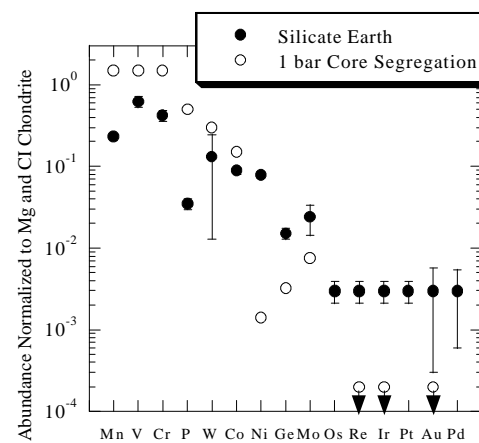
**Introduction:** Modern theory suggests that the accretion of large objects (>10–100 km's) to the primordial Earth would have caused large-scale melting resulting in an Hadean magma ocean [1,2]. Within the context of this model, segregation of metal from silicate to form the core may have occurred over a considerable range in temperature (1200 – >4000 K) and pressure (1 bar – > 30 GPa). If core segregation were a single-stage equilibrium event, then the abundance of 'metal-seeking' or siderophile elements (SEs) in the silicate Earth may reflect the conditions of equilibrium. In order to test the viability of the equilibrium magma ocean core segregation model (hereafter, EMOCS) it is imperative to know both the budget of SEs in silicate Earth and the metal/silicate partitioning behavior of SEs over a wide range of conditions. Here, I review the progress in experimental efforts to test the EMOCS model by experimental determination of metal/silicate SE partition coefficients, especially at high pressures and temperatures, since the Origin of the Earth meeting in 1988.

**Siderophile Elements in the Silicate Earth:** The abundance of SEs in samples of the crust and upper mantle have been used by many workers to constrain their budget in the silicate portion of Earth (see McDonough and Sun [3]). Chondrite normalized abundances for selected SEs in silicate Earth are shown on Fig. 1. It has proved to be a great challenge to develop physically realistic models that can explain the observed pattern, especially the near-chondritic Ni/Co and intra-platinum group element ratios.

Early attempts to account for the SE pattern assumed single-stage equilibrium metal segregation from a chondritic protolith at low pressures - a *homogeneous accretion model*. For example, Fig. 1 shows calculated SE abundances for such a model using experimentally measured partition coefficients at 1 bar [e.g. 4]; The calculated and observed abundances are mis-matched for essentially all elements, and some elements are in excess of calculated values by many orders of magnitude. This latter feature came to be known as the "excess siderophile element problem".

Sparked by the failure of the single-stage model to explain the SE pattern, a new class of models emerged that invoked a series of accretionary and metal-segregation stages (see [5]). These *heterogeneous accretion models* met with various degrees of success, although none could totally reproduce the SE pattern.

Another unsatisfactory aspect of these models is that the mode of accretion, essentially by gradual addition of relatively small objects and dust, requires little or no partial melting of the proto-Earth. This is clearly at odds with theoretical calculations which show that much of the kinetic energy from the impact of large accreting objects would be buried deep in the proto-Earth, causing large-scale melting and a global magma ocean [2].



**Fig. 1.** Siderophile element budget of the silicate Earth [3]. Also shown are calculated abundances for equilibrium core formation using 1 bar partition coefficients [4].

Once the concept of a global magma ocean gained credibility, homogeneous accretion again became plausible. Indeed, theoretical calculations showed that metal segregation from a magma ocean might occur as a metallic rain [6] and, due to small surface area to volume ratios, the metal droplets may equilibrate with molten silicate, possibly at high temperature and pressure. This prospect led to new theory and experiments that showed that both these variables might have significant effects on SE partition coefficients [7, 8], inspiring a flurry of new experimental studies.

**Experimental Determination of Metal-Silicate Siderophile Element Partitioning:** Two initial studies showed that pressure and temperature have significant effects on partition coefficients for some SEs [9, 10]. Subsequent systematic studies have been able to delineate the effects of pressure, temperature and composition on partitioning for many SEs, providing

the data needed to rigorously test the EMOCS model. For moderately siderophile elements (MSEs) there have been numerous recent studies for determining the solubility and partitioning behavior at conditions to  $>25$  GPa and  $>2800$  K [e.g., 9–14]. Righter et al. [14] used a large data set to parameterize the effects of intensive variables on partitioning for Fe, S, P, W, Co, Ni and Mo. They found that a reasonably good match to mantle abundances could be obtained for metal/liquid equilibrium at  $\sim 27$  GPa and 2200 K, perhaps at the base of a deep, albeit wet, magma ocean. Li and Agee [13] came to a similar conclusion on the basis of high pressure-temperature partitioning data for Ni and Co, although their preferred conditions of equilibration requires a temperature about 500 K higher, permitting a drier mantle. Presently, the EMOCS model seems reasonably successful in predicting the abundance of MSEs.

Highly siderophile elements (HSEs: Re and the Pt group elements) are present in silicate Earth at near-chondritic relative proportions, and some at absolute levels more than five orders of magnitude higher than predicted from solubility experiments at 1 bar [e.g. 15] (Fig. 1). To account for HSEs in an EMOCS model it is required that all HSEs become much less siderophile than at 1 bar. Further, partition coefficients must be the same for all elements at the conditions of equilibration; unlike 1 bar partition coefficients which vary by many orders of magnitude [15]. There are scarce data for the effects that intensive variables have on HSE partitioning, and known HSE chemistry makes it unlikely that varying intensive parameters will produce the necessary effects for all HSEs [15]. However, Righter and Drake [16] have shown that the metal/silicate partition coefficient for Re may have the appropriate value at a condition similar to that predicted from the MSEs. A difficult and immediate task is to measure HSE partition coefficients as a function of pressure and temperature. If the HSEs cannot be accounted for by an EMOCS model, then a late veneer of HSE-enriched material is probably necessary.

**Discussion:** Fig. 2 illustrates one possible EMOCS model. Accretion by giant impact(s) results in a deep global magma ocean. A silicate magma ocean floor forms as a consequence of the change in slope of the peridotite solidus from near zero at pressures just less than  $\sim 25$  GPa to highly positive at greater pressures [17]. Segregation of metal from the magma ocean occurs as a polybaric, polythermal, continuously equilibrating metallic rain, which collects and is ponded temporarily at the magma ocean floor. Recent experimental results on metal-silicate wetting angles indicate that liquid metal could percolate through a

perovskite-rich solid lower mantle [18], especially if a small amount of melt were present, perhaps collecting into sinking diapirs which do not re-equilibrate appreciably with the solid silicate. Many questions remain to be answered for this model, such as: 1) what are the chemical consequences of polybaric metal/silicate equilibration? 2) why is there no trace element or isotopic evidence for fractionation of a perovskite-rich lower mantle from upper mantle? 3) how can the previously formed core of a large impactor equilibrate with Earth's mantle?

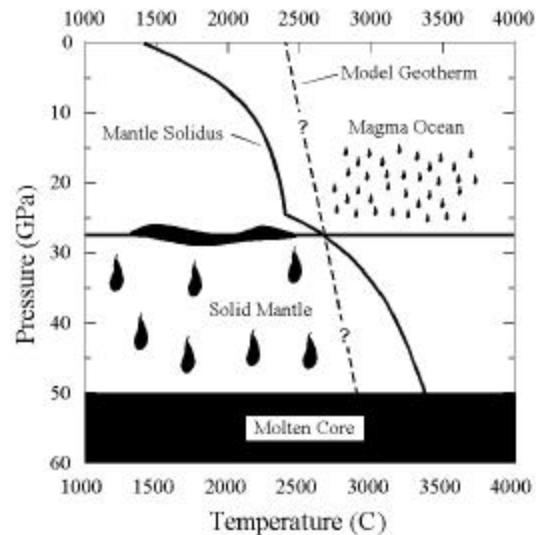


Figure 2. A schematic model of equilibrium magma ocean core segregation (EMOCS).

**References:** [1] Wetherill G. W. (1985) *Science*, 228, 877. [2] Benz W. and Cameron A. G. W. (1990) in *Origin of the Earth* (Newsom and Jones, eds.), Oxford Univ., p. 61. [3] McDonough W. F. and Sun S.-S. (1995) *Chem. Geol.*, 120, 223. [4] Schmitt W. et al. (1989) *GCA*, 53, 173. [5] Newsom H. E. (1990) in *Origin of the Earth* (Newsom and Jones, eds.), Oxford Univ., p. 273. [6] Stevenson D. J. (1990) in *Origin of the Earth* (Newsom and Jones, eds.), Oxford Univ., p. 231. [7] Murthy V. R. (1991) *Science*, 253, 303. [8] Keppler H. and Rubie D. C. (1993) *Nature*, 364, 54. [9] Walker D. et al. (1993) *Science*, 262, 1858. [10] Hillgren V. J. et al. (1994) *Science*, 264, 1442. [11] Holzheid A. et al. (1994) *GCA*, 58, 1975. [12] Walter M. J. and Thibault Y. (1995) *Science*, 270, 1186. [13] Li J. and Agee C. B. (1996) *Nature*, 381, 686. [14] Righter K. et al. (1997) *Phys. Earth Planet Int.*, 100, 115. [15] O'Neill H. St. C. et al. (1995) *Chem. Geol.*, 120, 255. [16] Righter K. and Drake M. (1997) *EPSL*, 146, 541. [17] Zerr A. et al. (1998) *Science*, 281, 243. [18] Shannon M. C. and Agee C. (1998). *GRL*, 23, 2717.

