

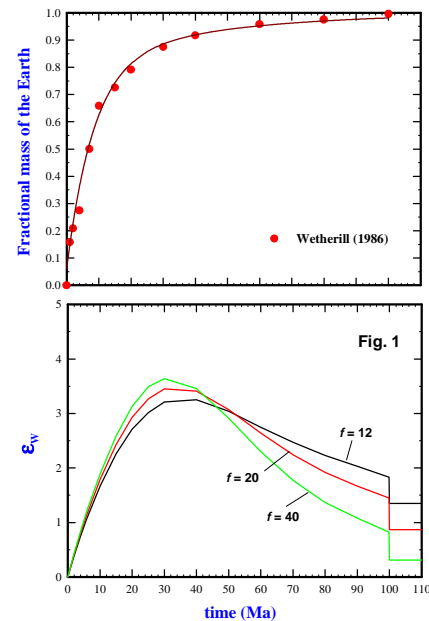
ISOTOPES AND METHODS FOR MODELING OF GEOCHEMICAL CYCLES. S. B. Jacobsen, Department of Earth and Planetary Sciences, Harvard University, 20 Oxford St., Cambridge, MA 02138 (jacobsen@neodymium.harvard.edu).

Introduction: The concept of geochemical cycles dates back to Goldschmidt [1] with his early version of the carbon cycle. He realized that man already had made a significant perturbation of this cycle due to fossil fuel burning. Barth [2] introduced the concept of residence time in a discussion of some of Goldschmidt's earlier work on geochemical cycles. Mason's [3] textbook included a general chapter on Geochemical cycles. The fundamental equations for the kinetics of evolving systems of reservoirs was discussed by Lotka [4] with applications to problems in biology. Lasaga [5] used such techniques for quantitative evaluation of geochemical cycles. The critical step is calculating the eigenvalues and eigenvectors of the geochemical cycle matrix (K).

Geochemical Cycle Models Based on Isotopes: Elemental cycles are usually modeled using a linear cycles approach with a K -matrix that is independent of time. The geochemical cycle matrix K is, however, in general a function of time, and better constraints on the dynamic evolution of the Earth can be obtained from radiogenic and stable isotope evolution of Earth reservoirs. For long-lived radionuclides the isotopic effects (ϵ) can be directly related to the mean age of the reservoir [6]. The radiogenic isotope evolution equations ($d\epsilon/dt = Qf + K\epsilon$; Q is a bulk Earth factor and f is the chemical fractionation of the parent/daughter ratio) can be used to constrain the K -matrix and thus the mass fluxes between all the reservoirs [7]. Examples of the application to stable isotope ratios (in particular $\delta^{13}\text{C}$) for constraining the C-cycle will also be given [8].

Accretion of the Earth: The extinct nuclide system ^{182}Hf - ^{182}W can be used to constrain the rate of accretion and core formation using these principles. The upper part of Fig. 1 (from [9]) shows the results of Wetherill's [10] accretion calculations (97.5 % of the Earth is made before 100 Ma and the last 2.5 % is assumed to be added at 100 Ma). This model yields a mean time of formation of 16 Ma for the Earth. The resulting isotopic evolution of W (ϵ_W) in the silicate portion of the Earth is shown for $f^{\text{Hf/W}}$ ratios of 12, 20 and 40 using a magma ocean differentiation model. In all cases the ϵ_W values show a peak at about 30 Ma. Subsequent to that time the ϵ_W value decays more rapidly for higher values of $f^{\text{Hf/W}}$. The last 2.5 % of accretion is sufficient to reduce the effect in the Earth to 1 ϵ_W unit or less. A variety of such models have the following features in common: i) they can produce a large early ϵ_W anomaly in the silicate Earth provided the

initial growth stage of the Earth is rapid (more than 50% formed in the first 20 Ma), ii) if substantial (>20%) growth of the Earth occurs subsequent to 20-30 Ma, then the ϵ_W anomaly is almost always reduced to less than 1 ϵ_W unit by 100 Ma, iii) late giant impacts



result in a ϵ_W anomaly of less than 0.5 ϵ_W units. It is necessary to have the Moon form by an early (~25 Ma) giant impact, while the Earth still had a substantial ϵ_W anomaly. At least 20 % of the Earth must have accreted subsequent to the formation of the Moon to effectively erase the ϵ_W anomaly in the silicate Earth. A scenario in which the Earth's core is formed after 60 Ma and the Moon simultaneously by giant impact is implausible.

References: [1] Goldschmidt, V.M. (1934) *Geol. Fören. Förh.*, 56, 416. [2] Barth, T.F.W. (1952) *Theoretical Petrology*, Wiley & Sons, Inc., 416 pp. [3] Mason, B. (1966) *Principles of Geochemistry*, Wiley & Sons, Inc., 329pp. [4] Lotka, A.J. (1924) *Elements of Physical Biology*, Williams & Wilkins Co, Inc., 465pp. [5] Lasaga, A.C., (1980) *GCA*, 44, 815-828, [6] Jacobsen, S.B. & Wasserburg, G.J. (1979) *J. Geophys. Res.*, 84, 7411-7427. [7] Jacobsen, S.B. (1988) *GCA*, 52, 1341-1350. [8] Jacobsen, S.B. and Kaufman, A.J. (1999) *Chem. Geol.* (in press). [9] Jacobsen, S.B., (1999) *LPSXXX*, Abstract #1978, [10] Wetherill, G. W. (1986) In *Origin of the Moon*, LPI, 519-550.