EVIDENCE FOR COLLISIONAL EROSION OF THE EARTH.

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Iron excess of the Earth. *The Fe/Mg ratio of the whole Earth is at least 10% higher than the Fe/Mg ratio of the average solar system.* Improved estimates of the chemical composition of the primitive upper mantle yield an MgO content of 36.33 ± 0.4 wt% [1], which transforms into a whole Earth Mg content of 14.90 wt%, assuming 32% for the mass of the core and that the core is Mg-free. The FeO content of the Earth's mantle is well established at 8.10 ± 0.05 %. Adding to this the Earth's core (85 wt% Fe) gives a whole Earth Fe content of 31.52 wt%. The resulting Fe/Mg ratio is 2.12. whereas the CI-ratio, representative of that of the solar system, is 1.92 ± 0.08 [2]. Thus the Earth has about 12 wt% more Fe than CI-meteorites and the average solar system. (The solar Fe/Mg ratio measured directly in the solar photosphere is 1.87±0.4; and is thus the same as the CI ratio, but its uncertainty is too large for this comparison to be useful). The Fe/Mg ratio of the whole Earth $(Fe/Mg)_{WE}$ can be written as:

$$(Fe/Mg)_{WE} = 2.3(1\text{-}Mg\#)/Mg\#+(Fe_c/Mg_{PM})*M_c/(1\text{-}M_c)$$

where Mg# is the molar Mg/(Mg+Fe) ratio of the mantle, 2.3 is the factor converting this to weight ratios, Fe_c is the Fe content of the core (here 85 wt%) and Mg_{PM} the Mg-content of the primordial mantle (here 21.9 wt%). The variation in Mg# of upper mantle rocks is from 0.888 to 0.896 [1] which introduces an uncertainty of only 1 % in $(Fe/Mg)_{WE}$.

The Fe content of the core: The 85% Fe assumed here is based on the traditional value of ~10 % for the light element inventory of the core. However in a recent reevaluation of the core density deficit, Anderson and Isaak [3] conclude that the difference between the observed density of the core and that of liquid Fe at appropriate temperatures and pressures is much less than previously thought. That implies a smaller light element inventory which in turn would further elevate $(Fe/Mg)_{WE}$.

The FeO and MgO contents of the mantle: Since the mantle contributes only about 13% of the Earth's inventory of Fe, variations in the FeO content of the mantle have only a minor effect on Fe_{WE}. Variations in Mg are more critical. There are two relevant issues: (a) the representative MgO content of the upper mantle and (b) chemical uniformity throughout the mantle.

The MgO content of the upper mantle calculated by O'Neill and Palme [1] is lower than many earlier estimates. Ringwood's pyrolite [4] had 38.1 %, which would reduce excess Fe from 12 to 6 %. And McDonough and Sun estimated 37.8 % MgO [5], leading to 7% excess Fe (and a higher than chondritic Fe/Al ratio [6]). PM (= primordial mantle) is a hypothetical concept and is therefore difficult to calculate precisely. Actual mantle rocks typically have more MgO than PM, reflecting depletion of fusible elements. The MgO content of the upper mantle of 36.33 wt% [1] is based on its Mg# of 0.89 and the surprisingly uniform FeO content, 8.07 ± 0.06 wt%, of primitive upper mantle rocks. This calculation does not assume any particular model to explain the observed chemical trends of upper mantle rocks, and is therefore more robust.

Uniformity of mantle composition: The major support for a chemically homogeneous mantle comes from geophysical constraints on whole mantle convection e.g. [7]. Radial differences in MgO and/or FeO would imply density differences that are unlikely to have been preserved in a globally convecting mantle over the age of the Earth. In particular, mantle with anomalously low FeO would be compositionally buoyant and should thus be relatively accessible to sampling at the Earth's surface. The absence of evidence for any such reservoir is therefore significant.

Another argument supporting a chemically homogeneous mantle is the inferred chondritic relative abundances of refractory elements (Al, Ti, Sc, REE etc.) in the primordial upper mantle, i.e., before crust extraction. This is inconsistent with postulated global melting and chemical differentiation of the silicate Earth, which would have severely fractionated these refractory elements [8].

Origin of excess Fe: The Earth makes up about 55 wt% of the inner solar system, most of the rest being Venus, which has the same density as the Earth. The FeO contents of venusian basalts are similar to primitive terrestrial basalts. These two observations suggest that the bulk FeO content of Venus is similar to the Earth's, although a precise estimate of the Fe/Mg ratio is not yet possible. Mercury, in contrast, has a huge Fe excess. Precise Fe contents for Mars and other minor bodies of the inner solar system are not yet available, but it is clear that there is no low-Fe reservoir in the inner solar system that might be complementary to the Earth.

There is no obvious reason why the material that condensed to form the inner solar system should have had as much as 10 % more Fe than the average solar system. The primordial mantle composition has many compositional similarities with carbonaceous chondrites, which, from type 1 to type 3 define a volatility sequence with decreasing contents of Mg, Si, Fe, Cr, Mn and all other moderately volatile elements, suggesting that carbonaceous chondrites and proto-Earth material experienced similar fractionations, controlled primarily or exclusively by nebular volatility [9]. However, volatility-related fractionation in the solar nebula would not lead to an abnormally high terrestrial Fe content, because Mg and Fe have similar nebular volatilities.

The growth of the Earth by accumulation of Moon- to Mars-sized embryos [10] could provide an explanation for the Fe-excess of the Earth. Presupposing the core had formed, early large impacts would preferentially remove mantle silicates. The amount of dispersed material is uncertain. It may be as much as several percent of the total mass involved in a collision [11]. Because the Earth is massive only relatively large impactors contribute significantly to this loss of silicates unless the process started early at a time when the Earth was not yet fully accreted but already differentiated. The present Fe excess can therefore be the integral results of many smaller impacts spread over the formation history of the Earth or the result of one or a few large collisions occurring at late time. An ultimate example of such a giant collision leading to a large loss of silicates has been proposed by Benz et al. [12] to explain the anomalous density of Mercury. In this case, nearly 80% of the mantle is lost in a single event!

Further evidence for the collisional removal of silicates from planetesimal sized bodies is provided by the huge impact crater near the south pole of Vesta that discovered by the Hubble Space Telescope. The volume of the crater corresponds to about 1 % of the mass of Vesta and most of it was lost. Binzel et al. [13] found in the vicinity of Vesta 20 small asteroids, each about 5 miles across, which had identical spectral reflectivity as nearby Vesta. They concluded that a large impact had blasted material off Vesta.

Apparently preferential loss of silicates can occur in planets or planetesimals of any size, provided there are already differentiated to some extent. With this reasoning all planets should have more or less excess Fe. The Moon is an exception as the bulk Moon Fe content is certainly below that of chondritic meteorites. However, if the giant impact hypothesis is correct, the Moon is the result of collisonal erosion of the Earth.

We point out that collisional erosion is particularly effective in the inner solar system where the relative collision velocities are likely to be the highest. Planets, such as Mercury should have experienced the largest loss of silicates while Venus should have a Fe/Mg ratio between Earth and Mercury. The latter point remains to be seen.

Consequences of collisional erosion: A number of geochemical consequences arise as a result of collisional erosion from a differentiated planet. Separation of metal from silicate to form a metallic core probably implies extensive melting of overlying silicates and thus the possibility of forming a primitive crust in which incompatible elements are concentrated. Preferential removal of this crust by collisional erosion would not only leave behind a planet with, for example, light REE-depleted patterns, but any bodies formed from the ejected material would display a complementary enriched pattern. Thus the almost axiomatic assumption in geochemistry that the Earth or the Moon has chondritic relative abundances of incompatible refractory lithophile elements must be questioned. Removal of an early terrestrial atmosphere is another consequence of collisional erosion which has been widely explored [14].

Summary: There is little doubt that bulk Earth has a Fe/Mg ratio that is higher than the solar (CI-chondritic) value. The Fe excess is at least 10%. It is attributed to preferential removal of silicates from the proto-Earth either directly, by large impacts, or indirectly, via impacts on differentiated planetesimals that subsequently accreted on the growing Earth.

References: [1] H.St.C. O'Neill and H. Palme (1998) In: *The Earth's Mantle: Structure, Composition and Evolution* pp. 3-126, Cambridge University Press. [2] Palme H. and Beer H. (1993) In: Landolt-Börnstein, Group VI: *Astronomy and Astrophysics* Vol. 3, Subvol. a, pp.196-221, Springer. [3] Anderson O.L. and Isaak D.G. (2002) *Physics Earth Planet. Int.* 131, 10-27. [4] Ringwood A.E. (1979) *Origin of the Earth and Moon*. pp. 295, Springer. [5] McDonough W. F., and Sun, S.-S. (1 995) *Chem. Geol.* 120, 223-253. [6] McDonough W. F. (2001) In: *Earthquake thermodynamics and phase transformations the Earth's interior* pp. 3-23, Academic Press. [7] Davies G.E. 1999, *Dynamic Earth*, Cambridge, University Press. [8] Kato T. et al. (1988) *Earth and Planet. Sci. Lett.* 89, 123-145. [9] Palme H. (2001) *Philosophical Trans. Royal Society,* 359, 2061-2075. [10] Wetherill G.W. (1994) *GCA* 58, 4513-4520. [11] Canup R. M. and Agnor C. B. (2000) In *Origin of the Earth and Moon*, pp.101-112. University of Arizona Press. [12] Benz W. *et al.* (1988) *Icarus* 74, 516-528. [13] Binzel P. and Xu S. (1993) *Science* 260, 186-191. [14] Pepin R. O. (1989) In: *Origin and Evolution of Planetary and Satellite Atmospheres* pp. 291-305. University of Arizona Press.