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Early Earth Evolution: Constraints from Combined Siderophile Element and Noble Gas Modeling

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Many geochemical traces of the earliest history of the Earth were obliterated due to collisions with large bodies and gravitational differentiation which caused convective mixing. However, two early processes, core segregation and loss of the early terrestrial atmosphere, were irreversible. The aim of this contribution is to discuss constraints on their nature, timing and duration. They are connected in the sense that core formation and the degassing of the silicate Earth resulted from - probably the same - magmatic processes. While siderophile element and noble gas relative abundances can give information on the nature of these processes, the Hf-W and Xe isotope systematics yield constraints on their timing.

The siderophile element abundance pattern of the silicate Earth can be reproduced by a model of quasi-continuous core formation during Earth accretion (Azbel et al., 1993; Kramers, 1998) or by a single segregation of metallic from silicate melt at high pressure (Righter and Drake, 1999 and references therein). The c.15 fold depletion of Xe in the Earth relative to the C1 normalized spectrum of other noble gases can be explained if it is postulated that magma degassing at low pressure was chiefly responsible for gas transfer of the early solid Earth to the atmosphere (Tolstikhin and O'Nions, 1994). The degassing can be modeled assuming melt production in the mantle lasting for c. 80 m.y. at rates of the order of $5x10^{19}$ g/yr as predicted by the quasi-continuous core formation models. We have not been able to model it using short lived deep magma oceans as a scenario.

In forward transport modeling of quasi-continuous core formation, constraints from Hf-W isotope systematics can be satisfied if c. 20% of Earth accretion occurred later than 60 m.y. after Allende, tailing off to 100 m.y. (Kramers, 1998). On the other hand, if core formation is modeled as a one-step segregation (Righter and Drake, 1999), this event must have occurred later than 60 m.y. after Allende (Halliday, 2000 and references therein). If the moon was formed by a giant impact event, the low metallic Fe content of the moon dictates that this should have post-dated such a segregation event. Problems then arise from the oldest ages on lunar rocks and the evidence of live ^{182}Hf in early lunar history (Halliday, 2000).

The terrestrial inventory of I-Xe systematics shows that about 99% of ^{129}Xe(I) generated in the Earth has been lost, therefore the earth-atmosphere system could not be closed earlier than 100 ±50 m.y. after Allende (The uncertainty stems from poor knowledge of I abundance in the Earth and the amount of ^{129}Xe(I) in less degassed reservoirs). Contrary to widely held views, I-Xe systematics alone do not yield an upper time (lower age-) limit for the loss event(s). A first order approximation for this limit is found by combining ^{129}Xe(I) and ^{136}Xe(Pu) systematics. ^{136}Xe(Pu) has been c. 20 times better preserved within the earth-atmosphere system than ^{129}Xe(I). Therefore, a major Xe loss must have occurred before the complete decay of ^{244}Pu. Because of the high loss rate required by the I-Xe systematics and the relatively long half life of ^{244}Pu, it must be concluded that the presently observed ^{136}Xe(Pu)$_{ah}$ was mainly accumulated after the time of atmosphere closure to Xe loss. From the initial ^{244}Pu abundance and the present-day inventory of Xe(Pu) in the Earth, the best estimate for this is 200 ±50 m.y. after Allende (Azbel and Tolstikhin, 1993).

Notwithstanding these time limits, terrestrial Pu-U-I-Xe constraints cannot be met with the assumption of a single atmosphere loss event. Forward modeling of the systematics in a quasi-continuous scenario assuming (a) intense Earth degassing up to about 75 m.y. after Allende, and rapidly decreasing after that time, (b) major atmosphere loss at, or up to, the same time, and (c) minor loss of atmosphere up to 250 m.y. after Allende, allows to reconcile Earth atmospheric ^{129}Xe(I) and ^{136}Xe(Pu) abundances as well as ^{136}Xe(Pu)/^{136}Xe(U) constraints. Thus successful quasi-continuous models for siderophile element abundances, Hf-W and Pu-U-I-Xe isotope systematics converge.

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