

Interactive comment on “Dynamical geochemistry of the mantle” by G. F. Davies

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In mid-90th it became clear that the earth mantle model envisaging separate convection flows in the upper (above the mantle transition zone between 400 and 660 km) and lower mantle reservoirs needs substantial revision. Studies based on (i) seismic tomography (Grand, 1994; Grand et al., 1997; Nataf, 2000; Romanowicz and Gung, 2001; Nolet et al., 2006), (ii) mantle convection models (Christensen, 1995; Puster and Jordan, 1997; VanKeken et al., 2002), (iii) evidence from trace element abundance in mantle rocks (Hofmann, 1997) indicate whole mantle convection and mixing, rather than separation of the mantle reservoirs.

Two “end-member” models were proposed to reconcile the earth chemistry (first of all, the chondritic earth model) with this new view on mantle dynamics.

(1) One considers a small enriched almost-completely isolated reservoir (instead of a

C101

large lower mantle), D” for example (Tolstikhin and Hofmann, 2005), as a hidden store of certain elements, such as LREEs, extraterrestrial (e.g., ³He) and early produced (e.g., ¹²⁹Xe(I)) noble gas species. Later on Tolstikhin et al. (2006) and Tolstikhin and Kramers (2008) have shown that the observations related to ²⁴⁴Pu – ¹³⁶Xe(Pu), ²³⁸U – ¹³⁶Xe(U), ¹²⁹I – ¹²⁹Xe(I), U-Th-He, ⁴⁰K – ⁴⁰Ar*, ¹⁴⁷Sm – ¹⁴³Nd, ⁸⁷Sr – ⁸⁷Rb, ¹⁷⁶Lu – ¹⁷⁶Hf, ¹⁸²Hf – ¹⁸²W isotopic systematics and the mantle abundances of moderately and highly siderophile (refractory) elements can be reconciled with their calculated abundances in the mantle, crustal and atmospheric reservoirs within the frame of the standard accretion (see Stevensen, 1987; Wetherill, 1990; Vityazev et al., 1990; Benz et al., 2000; Canup, 2004) and whole mantle convection (see references in the first paragraph) models. The underlying assumptions are: (i) D” reservoir was formed very early (soon after the giant impact, apr. 4500 Myr ago) from subducted basaltic (komatiitic) crust loaded by solar-wind implanted chondrite-like regolith; (ii) during subduction of this (relatively cold) material severe degassing and fractionation (caused mainly by slab dehydration and related melting) had not occurred because of absence of water on the earth surface at that time.

(2) Another set of chemical whole-mantle-convection models envisages heterogeneous mantle with mantle domains showing different degree of degassing, fractionation and mixing, so that some of these preserve, for example, low Sm / Nd ratios in the most fractionated domains, or low (U+Th)/³He ratios and thus low ⁴He / ³He ratios in the least degassed domains (e.g., Gonnermann and Mukhopadhyay, 2007).

The contribution by G. F. Davies “Dynamical geochemistry of the mantle” (hereafter DGM) belongs to “intermediate” models, in which some fractionated mantle domains (including those formed from “frozen” in the mantle undegassed melts, so called hybrid pyroxenites) swim in a convecting mantle (see the second end-member model above and Fig. 1 in DGM) and the others sink on the top of the core-mantle transition zone and lay there some time (see the first model).

I consider the DGM is a reasonable and useful (especially for students and teachers)

C102

review and it can be published in the Solid Earth. I especially enjoy in this paper clear and relatively simple qualitative estimates, such as the processing and residence times, the fractions of less processed materials, etc.

However, I propose the major revision of DGM in accord with the general comment.

General comment.

In this paper the “essential problem (of mantle dynamics, IT) and its resolution can be illustrated by helium” (see page 270, lines 23 – 25). From my point of view the only statement available from data on U-Th-He mantle systematic is that there are domains with different $^4\text{He} / ^3\text{He}$ ratio in the mantle, and some of these domains show $^4\text{He} / ^3\text{He}$ ratios substantially lower than the average MORB value. Assuming that extraterrestrial helium occurs in the mantle “since long”, in accord with observations presented by Tolstikhin et al. (1992), Richard et al. (1996), Matsumoto et al. (2002), then it is possible to extend this statement, i.e., the time-integrated (U+Th) / ^3He ratios are quite low in some of these domains, by a factor of ~ 100 lower than in a hypothetical average MORB-source depleted mantle (with the present-day $^4\text{He} / ^3\text{He}$ ratio of 8600 ± 2000 , see Graham, 2002). When these domains were formed and how they were developed can hardly be extracted from U-Th-He systematic, and this systematic is therefore useless for modelling of mantle evolution. Moreover, there are no reasonable constraints, following from U-Th-He data, neither on the initial He concentration in “early” mantle, nor on the rate of its degassing through time; what does it mean “early” or “since long” can also be extracted from *a-priori* data (models) only, but not from the U-Th-He data.

For example, if one ignores the standard earth accretion model and produces the earth from solar-wind implanted chondritic material (similar to Acfer H3-6 chondrite), then ^4He concentration in the “early” mantle could have been assumed at $0.01 \text{ cc STP g}^{-1}$ and $^4\text{He} / ^3\text{He}$ ratio at 2300 (Pedroni and Begemann, 1994); this exceeds the values presented in Table 1 (DGM, page 305) by a factor of apr. 1000.

If, in contrast, one follows the standard earth accretion from large already fractionated

C103

planetesimals (which contain negligible amounts of trapped noble gases and very little solar implanted ones), then the lower the initial amount of noble gas, required by a “dynamic mantle model”, the better (as during accretion the noble gas rich material is exceptional, while noble gas poor material is regular). Thus, to maintain the extraterrestrial helium flux in the mantle through all post-giant impact mantle evolution, the total amount of He required is by a factor of ~ 100 lower than that shown in the Table 1 in DGM (e.g., Table 28.3 in Tolstikhin and Kramers, 2008).

We used U-Th-He systematic in our model (Tolstikhin et al., 2006) in order to show, that the calculated parameters (including the initial ^3He and ^4He concentrations in the solar wind implanted materials) fit the observations within the frame of a scenario set by xenology.

In contrast to U-Th-He isotopic systematic, $^{244}\text{Pu} - ^{238}\text{U} - ^{136}\text{Xe}(\text{Pu,U})$ allows reliable constraint on mantle dynamics, and this constraint is **NOT** “readily accommodated in the models reviewed” in DGM (lines 25-28, p. 276). The initial “chondritic” $^{244}\text{Pu} / ^{238}\text{U}$ ratio (of the two highly refractory incompatible non-siderophile elements) in the silicate earth can be readily restored from meteoritic data (0.01 ± 0.005 , e.g., Azbel and Tolstikhin, 1993). Both chondritic and non-chondritic meteorites show very similar ratios thus indicating a similar behaviour of U and Pu in all fractionation processes. A similar value was derived from Xe isotope abundances in ancient terrestrial zircons (Turner et al., 2004, 2007). In a closed system formed 4570 ago the parent isotopes generate $^{136}\text{Xe}(\text{Pu}) / ^{136}\text{Xe}(\text{U}) \approx 40$, in sharp contrast to the ratio observed in the present-day mantle materials, from <0.2 (Phinney et al., 1978; Caffee et al., 1999) to <0.5 (Kunz et al., 1998; Yokochi and Marty, 2005). The only way to separate $^{136}\text{Xe}(\text{Pu})$ from $^{136}\text{Xe}(\text{U})$ is severe early mantle degassing, so that (approximately) only one ^{130}Xe atom of 10000 initially presented in the mantle has survived (see Fig. 6 in Tolstikhin and Marty, 1998, and related text; see also Yokochi and Marty, 2005).

All time scales and mixing – homogenization parameters are expected to be changed dramatically if a very high convection rate during the first 500 Myr of the Earth evolution

C104

is taken into consideration and therefore Specific comments (below) do not repeat this issue in numerous relevant Sections of DGM (e.g., 3.2, 3.2, 3.8, etc.) or lines devoted to these parameters.

My favourite proposal is to incorporate $^{244}\text{Pu} - ^{238}\text{U} - ^{136}\text{Xe}(\text{Pu,U})$ systematic in DGM, and then return to evaluating and discussion of this paper.

Another possibility is to constrain the subject of the review, for example “Dynamic geochemistry of the mantle during post-Hadean era” and remove from the paper text and figures related to the early earth evolution. Assuming a fairly homogeneous and almost completely degassed mantle at 4 Gyr ago, which becomes more and more heterogeneous later on because of decreasing of the rate of convection (in accord with the radioactive heat decreasing), probably allows most estimates of the parameters discussed to be preserved or slightly modified.

Specific comments

p255, l15-25. 4.5 – 4.0 Gyr ago the earth heat production was by a factor of ≈ 5 higher than at present; however, to remove $^{136}\text{Xe}(\text{Pu})$ from the mantle the melt flux at that time should be by a factor of ~ 100 above the present day value (see Fig. 28.2 in Tolstikhin and Kramers, 2008). Therefore, when xenology is included in DGM, these estimates are expected to be reconsidered. Also an independent estimate of the post-giant impact rate of convection gives ~ 1 month for a mantle domain to ascent from the core-mantle boundary to the earth surface (see related references and estimates in Section 17.5, Tolstikhin and Kramers, 2008).

p269, l14. Written: “. . . have cooled within only tens of thousands of years. . .” This is a minimum time scale and references must be included other than the author own contribution. For example, Abe (1993, 1997) considers time scales from 1 to 100 Myr. Xenology (see the General comment) requires fast convection on even longer time scale, up to 500 Myr (see Fig. 4 in Tolstikhin et al., 2006).

C105

p.269, l20. What does it mean “not completely homogenized” ? In such “quantitative” paper as DGM, a quantitative estimate of the homogeneity is expected.

p.269, l27-p270, l5. The amount of incompatible elements, stripped from solid phases by MORB magmas, is not an assumption, but it is the observation, as both MORB production and composition are known. Therefore the “hybrid pyroxenites” surrounded by depleted peridotite residue introduces some additional heterogeneities into the mantle, but do not change the bulk mantle mass balance of the incompatible elements. Instead, the mass balance of the incompatible elements in the terrestrial silicate reservoirs is mainly governed by subduction magmatism (see below).

P271, l25. The loss of ^3He atoms from the mantle is highly dependant on how and when the author introduces ^3He into the mantle. For example, if extraterrestrial He was introduced during the post giant impact accretion (at 4500 Myr ago), then from 10000 atoms introduced approximately 1 has survived, which is in sharp contrast to the “New estimates” in Table 1. If extraterrestrial He is introduced in the mantle during the late bombardment (4 Gyr ago), then the estimates in Table 1 appear to be more reasonable ones, even though I can not revise them with confidence as never modeled such a scenario.

P272, l5-l14. Instead of what is written here, I would argue that there is clear observational evidence on an extremely low $(\text{U+Th}) / ^3\text{He}$ ratio (and $(\text{U+Th}) / ^{22}\text{Ne}$ ratio) in the ^3He rich (or solar-like Ne rich) reservoir (see Fig. 2 in Moreira et al., 2001, Fig. 5 in Kurz et al., 2009). Again the author must say clearly, when and how the extraterrestrial noble gases were introduced in the mantle. If this happened ~ 4.5 Gyr ago, then this parent-daughter ratio in He (Ne) bearing reservoir should be by a factor ~ 100 lower than in the MORB source mantle (see Table 28.3 in Tolstikhin and Kramers, 2008). In this case addition of 1 % of its material into the subducted slab (sitting e.g., above this reservoir) changes dramatically concentration and isotope composition of He (Ne, and other noble gases). However, this small addition can not be detected by any other isotopic systematic irrespectively of the composition of He-rich reservoir: primitive, de-

C106

pleted (in incompatible elements by a factor of ~ 2 relative to the bulk silicate earth), or enriched by a factor of 3 (relative to the BSE, as D" in Tolstikhin et al., 2006). Therefore the composition and evolution of (subducted earlier) carrier of the "plume-like" helium plays a major role.

P273, I8-I9. The concentration of all incompatible elements in "hybrid pyroxenites" should increase in one and the same proportion. Assuming melt – solid partition coefficients for He, U, Th are similar, the (U+Th) / ^3He should not change considerably in the "pyroxenites", which means that $^4\text{He} / ^3\text{He}$ ratio in this reservoir would increase, due to decay of the radioactive parent isotopes, at the same rate as in MORB. Note that available estimates of the He partition envisaged similar (Heber et al., 2007) or even higher values (Hiyagon and Ozima, 1986) compared with U and Th. Thus, "hybrid pyroxenites", can not ensure rather low $^4\text{He} / ^3\text{He}$ ratios observed in some plume rocks and gases.

P275, I27. $^{40}\text{K} - ^{40}\text{Ar}^*$ systematic can say much less about the mantle degassing dynamics than $^{244}\text{Pu} - ^{238}\text{U} - ^{136}\text{Xe}(\text{Pu,U})$, especially if $^{129}\text{I} - ^{129}\text{Xe}(\text{I})$ duo is included into consideration as well.

P276, I25 – I28. What is written here in the text is simply not correct (see the general comment).

P283, I5-I10. Nothing is absolutely homogeneous in nature, but if we compare depleted MORB source mantle as expressed by the MORB compositions with other observable silicate earth reservoirs, the upper continental crust, the lower continental crust, and the subcontinental mantle lithosphere, the MORB source mantle is by far the most homogeneous reservoir, in accord with important contributions by Salters and Stracke (2004), and by Workman and Hart (2005).

P288, I25-I27. The overall depletion of the mantle reservoir depend on the initial composition of the bulk silicate earth (BSE) and the present-day abundances of an incompatible element in the continental crust (or/and in the mantle). Solution of the chondritic

C107

BSE model gives the depletion factor (amount in the mantle / total amount in the silicate reservoirs) for U at 40 % . If U available in the D" model reservoir + DMM is considered, then the depletion factor would be 60 % (see Table 28.3 in Tolstikhin and Kramers, 2008, and references therein). These values are in agreement with the preferred estimates in DGM (p.293, I5). Mantle depletion with the incompatible elements does not depend on peculiarities of melting and melt extraction in a given MOR magmatic event (therefore discussion of MORB magmatism in DGM is in some sense irrelevant and can be removed from the paper along with the Appendix 1), but on the complicated and poorly understood subduction-related processes, which efficiently extract the incompatible elements from subducting slabs and transferring them into the continental crust.

References. There are several quite important papers relevant to DGM, published, for example, by the Cambridge University group (O'Nions and McKenzie, 1998, Melt production beneath oceanic islands. PEPI, 107, 143-182; McKenzie, et al., 2004 Source enrichment processes responsible for isotopic anomalies in oceanic island basalts. GCA, 68, 2699-2724), by colleagues from the Columbia University (Langmuir et. al., 1992, Petrological systematics of mid-ocean ridge basalts: constraints on melt generation beneath ocean ridges. In: J.P. Morgan, D.K. Blackman and J.M. Sinton (Editors), Mantle Flow and Melt Generation at Mid-Ocean Ridges. Am. Geophys. Union, Washington, D.C., pp. 183-280). I think the Review benefits from including of these papers and other important papers into discussion and in References.

P305, Table 1: Reference on the "Conventional estimates" must be included.

P306, Table 2, footnote e: model-derived value of U concentration in D" was presented by Tolstikhin et al., 2006, Table 2.

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C108

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C109