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The Argon constraints on mantle structure.

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Abstract. The ^{40}Ar budget of the Earth offers a powerful and straightforward argument in favour of the existence of a layered structure to the mantle.

Whereas K-Ar-isotope systematics have been included as part of various discussions of mantle structure previously a simple and straightforward argument is presented here. Because ^{40}Ar is produced by ^{40}K the amount of K in the Earth may be constrained from ^{40}Ar budgets. The atmospheric ^{40}Ar budget implies that approximately half of all ^{40}Ar produced within the Earth since its formation is retained within the solid Earth. It is argued that this additional ^{40}Ar is located principally in the lower mantle.

Introduction

The abundances of radiogenic isotopes and trace elements have been used to constrain the structure and evolution of the Earth's mantle for a long time. Early efforts used the budgets of Sr and Nd and $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotope ratios [Allègre et al., 1979; Jacobsen et al., 1979; O'Nions et al., 1979; De Paolo, 1980] to argue for a layered mantle with separate convection in the upper and lower parts as suggested on the basis of geophysical arguments by Richter and McKenzie (1978). Subsequently, other radiogenic isotopes of lithophile elements including $^{208,207,206}Pb$, ^{176}Hf, ^{187}Os and trace element abundances were also used to address this question, and inverse techniques were employed to obtain refined estimates for the amount of depleted mantle [Allègre et al., 1983]. Finally, isotopic composition of rare gases were also found to consistent with a layered mantle structure (e.g. O'Nions and Oxburgh, 1983; Allègre et al., 1983; Allègre et al., 1986).

All of the above budget calculations were made with the assumption that the silicate Earth consists of three reservoirs: the continental crust of known mass and chemical and isotopic composition, a depleted mantle reservoir of known isotopic (though not necessarily chemical) composition and an undepleted or "primitive" reservoir of known chemical and isotopic composition. It should be noted that most of the estimates for the mass fraction of depleted mantle exceed the mass of the upper mantle, suggesting that convection in the upper mantle down to 670 km was probably not completely isolated from exchange with the lower mantle. In this case the lower mantle cannot have a primitive composition.

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Hofmann et al. (1986) showed that the trace element ratios Nb/U and Ce/Pb are indistinguishable between the MORB and OIB source regions and distinct to the respectivite primitive mantle values. This observation is important because it demonstrates that these lithophile elements in OIB are not derived from a primitive reservoir. A mass fraction for the "depleted" reservoir including MORB and OIB sources within the range 30 to 75 % of the mantle, was estimated from the budgets of these elements [Hofmann et al., op.cit.]

The present contribution has its origins in the early work of Turekian (1959) on the ^{40}Ar budget of the Earth, wich was extended by Allègre et al. (1983) and Turner (1989). The present analysis of the ^{40}K-^{40}Ar budget, previously presented in abstract form [Allègre et al., 1994] reaffirms the geochemical arguments in favour of two-layer mantle convection.

The K-Ar system of the Earth

^{40}Ar in the Earth is almost entirely produced by the decay of ^{40}K. Its atomic weight is too high to allow its escape from the Earth's atmosphere, and under normal conditions it will be retained after the Earth accreted. Because ^{40}K has decayed over 4.5 10^9 yr of Earth history, the amount of ^{40}Ar produced during this time can be calculated if the K content of the Earth is known. The amount of ^{40}Ar produced in 4.5 10^9 yr is equal to 1.16 ^{40}K present in the bulk Earth today. The K content of the Earth may be estimated assuming that K/U = 12,700, by weight [Jochum et al., 1983], which is the MORB ratio, taken with the uranium content of primitive mantle. For a U abundance in the range of 20 and 22.5 ppb (e.g. Ganapathy and Anders, 1974), then the corresponding K-content is between 250 and 285 ppm. These values correspond respectively to the production of 140 10^{18} g and 156 10^{18} g of ^{40}Ar in the Earth since 4.5 10^9 yr.

The amount of ^{40}Ar residing in the atmosphere is 66 10^{18} g [Turekian, 1959]. The ^{40}Ar content of the continental crust is unknown from observation but if, for example, it has been a closed system with a mean age of 2 10^9 yr then the amount of ^{40}Ar produced in the continental crust is around 9 10^{18} g for a K-content of 1.7 %. An upper bound would be a mean age of 2.7 10^9 yr and a K-content of 2 %, leading to ^{40}Ar = 12 10^{18} g. [Allègre et al., 1986]. A lower bound should allow for degassing, which may be as much as 50 % and lead to proportionately lower estimates. In effect therefore, much of the ^{40}Ar produced in the continental crust is now part of the atmosphere inventory.

Therefore, some 63 10^{18} to 80 10^{18} g of ^{40}Ar resides elsewhere in the interior of the Earth and this represents about 50 % of the total ^{40}Ar produced geological time. Recent experiments [Matsuda et al., 1993] have shown that the partitioning of rare gases between metal and silicate even at high pressures strongly favours the silicate phase. Indeed if

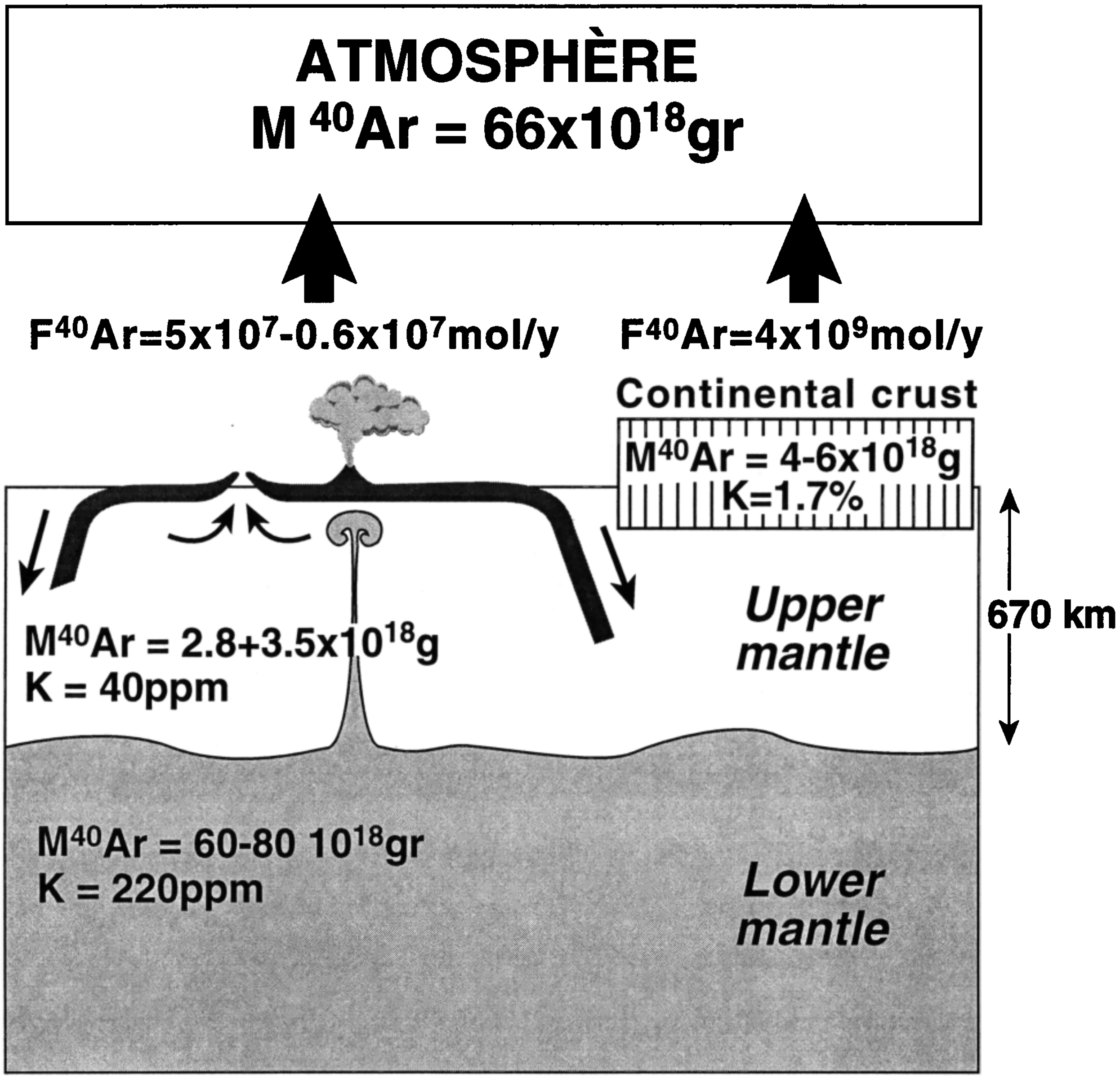

Figure 1. This figure gives a representation of a coherent model for distributing ^{40}Ar and ^{40}K in the Earth. F and M represent the fluxes in moles/year and mass in grams, respectively.

the "missing" ^{40}Ar is in the core then it should have a K-content of 500 ppm - well outside any estimates made so far.

Therefore the mantle should contain about 50 % of the terrestrial ^{40}Ar budget. The distribution of ^{40}Ar is now considered in the framework of two layer and single layer mantle convection using two independant estimates for mantle ^{40}Ar, one devided from the upper mantle K content, the other from estimates of the ^{40}Ar flux through the ocean ridges.

Potassium content

The K content of MORB is typically 500 ppm [Jochum et al., 1983]. For a degree of partial melting between 8 to 10 %, as estimated from petrology or geochemistry [Klein et al., 1987; Hofmann, 1988], we obtain a present day mantle source K concentration of 40 to 50 ppm. If this value is used for the whole mantle, it leads to some 22 to 28 10^{18} g of ^{40}Ar produced in the mantle over 4.5 10^9 yr, considerably less than the 63 to 81 10^{18} g of ^{40}Ar assumed to be present in the mantle from the above considerations.

Alternatively if the mantle is layered at the 670 km seismic discontinuity, then the amount of 10^{18} g of ^{40}Ar produced in the upper layer is only 7.3 to 9.3 10^{18} g. In this case some 54-74 10^{18} g of missing ^{40}Ar will be in the lower mantle - this corresponds to about 230 ppm of K in the lower mantle.

^{40}Ar flux

An estimate of the ^{40}Ar flux from the world's ridge system can also be used to constrain the ^{40}Ar abundance in the MORB source. The total ^3He flux is 1.1 10^3 moles/yr [Craig et al., 1975], and the corresponding ^4He flux is 9.46 10^7 moles/yr for a $^4He/^3He$ = 8.6 10^4 at the ridges [Craig et al., 1976; Kurz et al., 1982]. The $^4He/^{40}Ar$ ratio in MORB varies between 2 and 15 [Sarda et al., 1985; Allègre and Lewin, 1989; Staudacher et al., 1989], which corresponds to an ^{40}Ar flux of 5 10^7 and 0.63 10^7

moles/yr, respectively. This Ar flux corresponds to the outgassing of the oceanic lithosphere by melting at the ridge crests. Oceanic crust is produced at 3 km^2/yr and for a lithosphere thickness of 60 km with a mean density of 3.2 g/cm^3. Thus the mass of oceanic lithosphere passing through the ridge system is 5.76 10^{17} g/yr. If this volume of material is completely outgassed at the ridge crest, then the ^{40}Ar flux estimate may be used to compute the concentration of ^{40}Ar in mantle material. Given a mantle mass of 4 10^{27} g the ^{40}Ar content of the mantle is 1.4 10^{18} g and 1.8 10^{18} g respectively, for $^4He/^{40}Ar$ ratios of 2 and 15 respectively. Both values are much lower than the 63 to 81 10^{18} g required from above. Indeed this is even smaller than the estimate based on potassium content.

For a two layer model, the amount of ^{40}Ar stored in the upper mantle (above the 670 km seismic discontinuity) may be estimated in the same way, to give a range of 0.6 to 4.6 10^{18} g. The corresponding amount of ^{40}Ar in the lower mantle is then at least 59 10^{18} g ^{40}Ar which corresponds to a K concentration of about 230 ppm as obtained previously.

Conclusions and discussion

In summary, two different arguments based on K and Ar in MOR basalts and consideration of ^{40}Ar flux at ridges suggest a low ^{40}Ar mantle while considerations of the total ^{40}Ar budget necessitate a relatively large concentration of ^{40}Ar inside the Earth. Because it is unlikely that the core has a high ^{40}Ar content, this mismatch is most readily reconciled by a two layer mantle with an upper mantle outgassed in ^{40}Ar and a lower mantle relatively undegassed in ^{40}Ar.

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