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Growth of the Earth's Core as a Source of Its Internal Energy and a Factor of Mantle Redox Evolution

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Abstract—We consider a model for core growth (5% of the original core accretionary mass) during geological evolution. It is suggested that this process occurred at the expense of FeO dissolution that was supplied to the core boundary by a descending limb of the mantle convection flow. This process could provide heat emission, which would eliminate the imbalance between the observed heat flow and the total energy of radioactive elements. The process also maintains the superadiabatic temperature gradient necessary for convection. Oxygen disproportionation due to FeO dissolution lead to an oxygen influx into the mantle, thereby providing its oxidation evolution.

The redox state of the mantle is a topic of active scientific debate. There is evidence that the mantle redox potential is heterogeneous and variable in space and time. Some investigators believe that the mantle evolves from a reduced to a more-oxidized state [1–3] and that such an evolution is related to the subsidence of the relatively oxidized oceanic crust into the mantle [2]. We set this problem in the context of carbon-bearing fluid migration from more-reduced toward more-oxidized mantle areas. This process provides isotope fractionation and may explain the observed regularities in carbon isotope distribution in diamonds. Mantle redox evolution is able to explain temporal variations in the conditions of diamond formation [4].

So far, the problem of the sources of Earth's internal energy was not regarded to be especially pressing. Heat flow from the Earth's interior is 4×10^{13} W [5]. The energy of the decay of radioactive elements (^{235}U, ^{238}U, ^{232}Th, and ^{40}K) is of the same order of magnitude (2.4×10^{13} W) as that of the heat flow. The observed imbalance may be partly ascribed to incorrect knowledge of element abundances in the Earth. In addition, a tremendous amount of energy was stored during the Earth's formation. This energy consists of the gravitational energy of accretion and differentiation, including that due to core formation, and heat released during the decay of short-lived isotopes (^{26}Al, for example). The accurate calculation of this energy is difficult, because the mechanism and conditions of the accretion remain unknown. In any case, it could account for a significant (though uncertain) contribution to the terrestrial heat flow.

However, concepts prevailing for the last two decades on global convection as a driving force of geodynamic processes direct more attention to the problem of energy sources.

The fact is that convection leads primarily to the rapid transfer of internal heat toward the surface. Hence, the primary heat accumulated during accretion should have been exhausted during a geologically short time. This source may play only a subordinate role in the balance of the modern heat flow. Moreover, a temperature gradient is needed to maintain convection. This means that, if convection entrains the whole mantle, the heat source should be located in its bottom, at the core–mantle boundary. The major radioactive elements—U, Th, and K—are lithophile elements with large ion radii and an affinity to melts. Accordingly, they were removed by melts toward the surface and accumulated at the upper parts of the lithosphere during geologic history.

The opinion that we do not know the exact contents of radioactive elements is presumably exaggerated. U and Th are refractory elements. Ratios of refractory elements are planetary constants. The rock-forming elements Ca, Al, and Ti are also refractory. Their abundance in the Earth was determined fairly reliably with an error probably below 10%. Therefore, the abundances of U and Th were determined with the same error. K is geochemically similar to U, hence the K/U ratio in rocks is fairly constant: for terrestrial rocks, it is close to 3000.

This indicates that the difference between the observed value of heat flow (4.0×10^{13} W) and its fraction due to radioactive decay (2.4×10^{13} W) is presumably significant and requires explanation.

In this paper, an attempt is made to link possible solutions for the problem of sources of the Earth's internal energy and that of the redox evolution of the Earth's mantle.

Calculations show that the contribution of such heat sources as phase transformations in the mantle (for example, olivine–spinel transition, etc.), tidal interaction with the Moon, and crystallization of the inner core, is low and does not exceed 0.1×10^{13} W [6]. However, there is a process, which could provide permanent emission of a considerable amount of heat comparable with that of radioactive decay. This is the growth of the Earth's core. This problem was first analyzed in detail by Sorokhtin [7]. However, his model suggested the absence of a core in the incipient planet, its subsequent initiation 400 Ma after accretion, and complete generation at 2.5–2.9 Ga. Such a scheme seems to be hardly probable.

At present, it is accepted that the Earth's core was formed mainly at an early stage, practically during accretion [8]. This assumption is supported by the remnant magnetization in the oldest rocks (3.5 Ga) and no more than two-fold variations in the highest intensity of the magnetic field in various geologic epochs [9, p. 94]. No significant variations were observed in siderophile element abundances in rocks during geologic evolution. So, we suggest that core formation was neither late, nor long, but only the growth of the original core occurred in the course of the process that was not related to iron segregation in the mantle and the descent of the metallic phase into the core, as was proposed in the models of the formation of the original core. The latter process must necessarily have lead to a mantle depletion in siderophile elements.

The core growth could proceed through the dissolution of FeO that was transported into the core by the descending limb of convective mantle flow. According to geophysical data, the Earth's core contains, in addition to Fe and Ni, up to 10–12% of a light element. H, Si, S, and O were proposed as such an element. The solubility of FeO in metallic iron is known to depend strongly on pressure. It becomes significant (more than 10%) only at pressures above 300 kbar. At $P = 600$ kbar, FeO solubility in iron is as high as 54 mol %. Hence, this process is efficient only in fairly large bodies. In the Moon, for example, pressure in the center is only 50 kbar and the role of this process is negligible. To the contrary, in the Earth, pressure at the core–mantle boundary exceeds 1350 kbar and this process should be significant.

This process results in the replacement of a mantle layer by a core layer (ΔR). As a result, mantle mass decreases (parallel to an increase in the core mass) by the value:

$$\Delta m = 4\pi R_c^2 \Delta R(\rho_c - \rho_m), \qquad (1)$$

where R_c is the current core radius, and ρ_c and ρ_m are the densities of the core and mantle, respectively, at the mantle–core boundary.

Energy ΔE released as a result of migration of the mass Δm toward the core surface may be estimated with simplification as follows:

$$\Delta E = \Delta m g h, \qquad (2)$$

where h is the weighted mean of mantle height above the core surface.

From this equation, core growth in a time unit is

$$\Delta R = \frac{\Delta E}{4\pi R_c^2(\rho_c - \rho_m)gh}. \qquad (3)$$

The above-mentioned heat deficiency (approximately 1.5×10^{13} W) corresponds to the annual generation of energy $\Delta E = 4.6 \times 10^{27}$ erg at $R_c = 3.5 \times 10^8$ cm and $h = 1.8 \times 10^8$ cm. According to the PREM model, $g \cong 1000$ cm/s^2 throughout the whole mantle profile, $\rho_c = 10$ g/cm^3, and $\rho_m = 5.6$ g/cm^3 [6].

The calculation gives $\Delta R = 3.8 \times 10^{-3}$ cm per year. Hence, a core growth of only 170 km (one-twentieth fraction of its radius) during all geologic history provides energy sufficient to account for the observed deficiency (if, for simplification, the flow is assumed to be constant).

As follows from (1), the annual increase of the core mass is $\Delta m = 4\pi(3.5 \times 10^8)^2 \times 3.8 \times 10^{-3}(10-5.6) = 2.5 \times 10^{16}$ g. At the constant growth rate, the core mass increased by 1.1×10^{26} g during the Earth's history, that is, 5.7% of a modern core mass of 2.0×10^{27} g. This estimate is approximate, because a precise calculation must account for temporal variations in masses and sizes of the core and mantle, as well as heat evolution and the geodynamics of the planet. Such calculations are hardly possible and probably would not result in corrections of model parameters above 5–10%.

An increase of 5–10% in the core mass should not apparently result in significant changes of the magnetic field intensity. It could not also affect significantly the abundance of siderophile elements. Moreover, the partition coefficients of siderophile elements between silicate melt and Fe_2O melt at core–mantle boundary pressures may significantly differ from values experimentally obtained for the silicate–metal system at much lower pressures. This problem requires an additional study.

It should be noted that the proposed model not only solves the problem of energy sources, but also provides a fundamental condition for the maintenance of mantle convection. In this case, heat emission is confined to the base of the mantle and provides a superadiabatic gradient necessary to maintain the convection.

Another important aspect of the process under consideration is that it assumes the redox evolution of the mantle and implies a mechanism for such an evolution.

If oxygen is the major light element of the core, its content of 10–12% approximately corresponds to the Fe_2O formula.

FeO dissolution in the core may be described by the reaction:

$$FeO + Fe \longrightarrow Fe(FeO). \qquad (4)$$

However, the contact between the convecting mantle and core may lead to oxygen disproportionation:

$$2FeO \longrightarrow Fe_2O + O. \qquad (5)$$

Wüstite disproportionation into metallic Fe plus magnetite at high pressure was experimentally obtained [10].

An increase in core mass via reactions (4) and (5) by 1.1×10^{26} g is accompanied by the extraction of $(1.1-1.25) \times 10^{26}$ g FeO from the mantle. This corresponds to ~3% of the mantle mass (4×10^{27} g), that is, FeO content in the oldest mantle was 3% higher than in the modern one.

The highest amount of oxygen, which could be transported into the mantle during geological history according to reaction (5), is 0.14×10^{26} g. At present, the oxygen fugacity of the upper mantle is close to the QFM buffer and corresponds to a Fe^{+3}/Fe^{+2} ratio of approximately 0.02 [2]. To obtain such a ratio at an initial abundance of ferrous iron in the mantle of 8%, 0.1×10^{25} g oxygen is necessary. It is evident from these calculations that reaction (5) supplies enough oxygen to change the redox state of the whole mantle from IW to QFM.

Rigorous estimate of the balance is hampered by the existence of buffers of unknown volume, primarily carbonaceous. Exact carbon abundance in the mantle is unknown. Various authors reported estimates from 0.007 to 0.1%. The latter value corresponds to a carbon content of 4×10^{24} g in the mantle. If original carbon occurred in an elemental state, then its oxidation would require 0.11×10^{26} g of oxygen. In addition to carbon oxidation, part of the oxygen supplied to the mantle could be used for the oxidation of residual metallic Fe. Moreover, if CH_4 and H_2 occurred in addition to elemental carbon, a certain fraction of oxygen should be used for hydrogen oxidation and water formation. In any case, it is apparent that the oxygen mass due to core growth is of the same order of magnitude as oxygen sinking into the consuming reservoirs. This inevitably should result in the oxidation of the mantle and external layers of the Earth during geologic time.

In principle, this process has a limitation. Equilibrium in reaction (5) apparently corresponds to certain oxygen fugacity. Its value for conditions at the core–mantle boundary is unknown, however the attainment of such a level will terminate the oxygen flux into the mantle, and core growth would be related only to the process of dissolution according to reaction (4). It is possible that the QFM oxidation state of the upper mantle corresponds to this case. This means that the distribution of redox potential in the mantle reached a stationary state at a certain moment of geologic history.

CONCLUSIONS

Energy sources usually considered (radioactive decay, heat conserved during planet formation, tidal energy, energy of phase transitions, and energy released during core crystallization) do not explain the observed values of the energy consumption under the convecting mantle conditions.

The deficiency may be eliminated within the concept of continuous core growth during geologic history that resulted from FeO transfer from the mantle into the core with simultaneous oxygen disproportionation.

The proposed model allows us to obtain consistent solutions for a number of modern problems: energy balance of the Earth, maintenance of the superadiabatic temperature gradient providing mantle convection, and oxidation evolution of the mantle.

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