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Global water cycle and Earth's thermal evolution

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Abstract

Convergent margin processes play an important role in the distribution of terrestrial volatile species. During subduction processes volatiles are filtered from the subducting package and are restricted to return to the mantle. Water is the most abundant volatile and plays an important role in these processes. There is a number of geochemical investigations to determine the subduction, regassing, and recycling fluxes as well as the regassing ratio of water. The latter describes the partition of subducting water by water that is regassed into the mantle and water that is returned to the surface in arc magmas. Here we present a geophysical-based modelling approach for the calculation of such fluxes and ratios in order to compare them with the geochemical data. In order to assess the recent values and the evolution of the subduction, regassing, and the recycling flux a simple parameterized thermal convection model with a water-dependent rheology and a constant continental growth model is applied. To test the sensitivity of the results different continental growth models were applied and the total amount of water in the system was varied as well as the initial distribution of water in the reservoirs. According to our estimations a value of 0.31 for the time independent regassing ratio of water, R_{H_2O}, is an acceptable upper bound. Lower values of R_{H_2O} give larger water reservoirs on the surface compared to the recent situation. Larger values of R_{H_2O} suggest smaller surface reservoirs of water and, therefore, seem to be unlikely. The model results show a relatively stable value for the regassing ratio of 0.31 by varying the initial conditions of the water distribution in the reservoirs (which are pretty much unknown at the present moment). But R_{H_2O} is very sensitive towards the total amount of water in the system. Altering the value of four ocean masses to ten we get values for the regassing ratio from 0.31 to 0.89. Nevertheless, as a result of all numerical experiments the recent subduction flux is stable and equal to 1.02×10^{15} g/a. The influence of the continental growth model on the results could be neglected. The calculated value for the recent subduction water flux fits the modern geochemical data very well while our value for R_{H_2O} is smaller. One possible reason could be that in our experiments R_{H_2O} remains constant and, therefore, represents an average value over Earth's history. In order to check this assumption we apply a simple exponential time dependence of R_{H_2O}. Here, the modern regassing ratio increases to 0.41. Therefore, based on a geophysical modelling approach in contrast to the geochemical

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investigations we suggest a smaller value for the modern regassing ratio of about 0.3 to 0.4.

1. Introduction

In the framework of modern physics, planet Earth can be considered as an open system with processes of self-organization and evolution. The main forcing of these processes is the solar radiation of about 1.2×10^{17} W with an effective temperature of 5770 K. This short wave radiation heats up the surface layers and the Earth emits long wave radiation with an effective temperature of 257 K into the space. This corresponds to an export of entropy of about -6×10^{14} W/K (Landau and Lifschitz, 1971; Ebeling and Feistel, 1982). In this way, the short wave insolation is the most important "pump" of entropy for the process of self-organization on our planet influencing also the biological evolution. The investigation of simple open systems like Bernard-convection or chemical oscillations shows the result that structure formation is connected both with the export of entropy and with the cycling of matter. Concerning the Earth system, the components rock, water, air, and organic matter also interact with each other and form structures by cycling processes.

However, on very long time scales, the steady-state character of cycling processes fails because of long-term evolution. For the Earth system there are two main processes of long-term evolution: the increase of solar luminosity and the Earth's thermal evolution by cooling of the interior. Both processes provide a certain direction for the evolution of the system and cause a deviation from steady state. The increasing solar luminosity of about 10% per Ga forces cycling processes of self-regulation and determines the life span of the biosphere (Franck et al., 2000). The evolution of the global mean terrestrial heat flow is connected with a secular cooling of the Earth's mantle of about only 250 K since the Archaean and a strong coupling between thermal evolution and degassing history (Franck, 1998).

The idea of cyclic processes in geology was very important for the development of scientific thinking. The eighteenth century was a time of rationalism and discovery. The Neptunists developed the idea that in the early stages of its evolution the Earth was covered by a universal ocean and the present continents have emerged by secular lowering of the sea-level. A famous Neptunist was A. G. Werner according to whom the Earth's crust had been laid down as a series of worldwide formations by a primeval ocean. Thus the face of the Earth had been built and shaped mainly by the agency of water. In the opinion of the Plutonists rocks were mainly the results of recycling of material derived from erosion of older rocks. According to J. Hutton the products of erosion accumulated on the sea floor where they became hardened by the Earth's internal heat. In this way, the Neptunist–Plutonist controversy of the eighteenth century already covered two general features of scientific thinking, the repetitious cycling of planetary matter on the one side and the directional evolution of the Earth on the other side.

In the present paper we are concerned with the global water cycle and the thermal evolution of the Earth. With respect to the discussion above, we are concerned with cycling of matter representing certain structures in the general sense and with a certain direction resulting from the Earth's thermal evolution.

Based on detailed scenarios of the processes that formed the Earth and other terrestrial planets (see e.g. Newson and Jones, 1990) a steam atmosphere probably formed by impact degassing during accretion and the surface was covered with a magma ocean (Matsui and Abe, 1986; Zahnle et al., 1988; Franck, 1992). With the decrease in the impact energy flux the steam atmosphere became unstable and the water condensed to form the proto-ocean (Abe and Matsui, 1988). Because the solubility of water in silicate melts is rather high, we can expect noticeable amounts up to 0.35 wt.% of water in the mantle (Liu, 1988). Other estimates for the present amount of water in the mantle result from various investigations. Ringwood (1966, 1975) estimates about 0.1 wt.% from the pyrolite mantle model as a lower bound. Wänke et al. (1984) and Jambon and Zimmermann (1990) give similar values resulting from mantle nodules and measurements of K_2O/H_2O ratios, respectively. According to Ahrens (1989) the amount of water in the mantle is greater than 0.07 wt.% based on his Earth accretion model. A mantle water content of about 0.1 wt.% corresponds to about 3 ocean masses of water in the mantle or all together 4 ocean masses of water in the Earth system. There are also investigations that give rather low values for the present mantle volatile content. Kuramoto and Matsui (1996) estimated less than one ocean mass of water in the present mantle. Kasting and Holm (1992) give arguments for a dynamic regulation mechanism involving exchange of water between the crust and the mantle and explaining why continental freeboard has remained approximately constant since the Archaean despite the increase in continental area.

The thermal history of a planet mainly depends on the initial mantle temperature, the distribution of radiogenic heat sources, and the mechanism of heat transport within the mantle. It is generally accepted that subsolidus convection is the dominant mechanism of the heat transport within the mantle. Temporal variations of the average mantle temperature and the surface heat flow in terms of the Rayleigh number can be calculated under certain initial conditions with the help of parameterized convection models (Franck and Bounama, 1995a and the references given therein). The Rayleigh number mainly depends on the kinematic viscosity of the mantle which in turn depends on both the temperature and the volatile content of the mantle. In order to introduce this effect into these models McGovern and Schubert (1989) have parameterized the activation temperature for solid-state creep as a function of water weight fraction. A different approach to that problem could be the use of experimentally derived results, describing the effect of water fugacity on the deformation of olivine. The results indicate a higher fugacity of water and hydrogen under wet conditions in contrast to that under dry conditions. Karato (1989) suggested a power law dependence between creep rate and water fugacity. Franck and Bounama (1995b) used such a relation in order to introduce a volatile dependent rheology into evolution models.

In our investigation we test a parameterized convection model under internally heated mantle conditions. A whole-mantle convection and the dependence of viscosity on both temperature and volatile content is assumed. We are particularly interested in the processes in subduction zones, where water from the subducting slab is partly lost by back-arc volcanism and andesitic volcanism to the atmosphere and partly retained in subducted rocks recharging the mantle. The main intention of this investigation is to calculate fluxes characterizing this partition process. Up to now such investigations of the volatile fluxes in subduction zones are exclusively based on geochemical studies (e.g. Bebout, 1995; Hadfield, 1999; Javoy, 1997; 1998; Leeman, 1996; Peacock, 1990; 1993; 1996; Ryan et al., 1996; Turner and Hawkesworth, 1997).

In Section 2 we present our parameterized convection model with volatile exchange and describe the degassing and regassing processes in detail. The results of our numerical experiments are given in Section 3. In the last section we discuss our results and compare them with results from other investigations, mainly from isotope geochemistry. Furthermore, we try to discuss some general aspects about the future surface water reservoirs.

2. Parameterized convection models with degassing and regassing

Parameterized convection models have been developed for more than 25 years (e.g. Tozer, 1972; Schubert, 1979). They are applied to study the temporal variations of such quantities as average mantle temperature and heat flow by parameterizing the heat flow in terms of the Rayleigh number Ra:

$$N \propto Ra^{\beta}, \tag{1}$$

where N is the ratio of the total heat flow and the conductive transported heat (Nusselt number) and β is an empirical constant, usually equal to 0.3 (Schubert et al., 1980).

The effect of volatile-dependent rheology on the thermal evolution of the Earth was analysed for the first time by Jackson and Pollack (1987). They have shown that the existence of volatiles have a significant effect on the thermal history of the mantle.

In order to calculate the exchange of volatiles and to investigate the feedbacks existing between heat transport and volatile-dependent viscosity, a self-consistent model was first presented by McGovern and Schubert (1989) and developed further by Franck and Bounama (1995b). The main idea is a coupling of the thermal and degassing history of the Earth with the help of simple relations from boundary layer theory (Turcotte and Schubert, 1982):

$$q_{\mathrm{m}} = \frac{\sqrt{S}\, 2k(T_{\mathrm{m}} - T_{\mathrm{s}})}{\sqrt{\pi\, \kappa\, A_0(t)}}, \tag{2}$$

where q_{m} is the mean heat flow from the mantle, S is the seafloor spreading rate, k is the thermal conductivity, κ is the thermal diffusivity, T_{m} is the average mantle temperature, T_{s} is the surface temperature, and $A_0(t)$ is the area of ocean basins at the time t. $A_0(t)$ can be used to introduce different continental growth models (Franck, 1998; Franck et al., 2000). In the evolution model, water from the mantle degases at mid-ocean ridges from a certain volume (degassing volume) that depends on the seafloor spreading rate S and the melt generation depth d_{m}:

$$(\dot{M}_{\mathrm{mv}})_{\mathrm{d}} = \varrho_{\mathrm{mv}} \cdot d_{\mathrm{m}} \cdot S, \tag{3}$$

where $(\dot{M}_{\mathrm{mv}})_{\mathrm{d}}$ is the degassing rate of water at mid-ocean spreading centres and ϱ_{mv} is the density of water in the mantle (mass of mantle volatiles M_{mv} per mantle volume).

The rate of regassing of water at subduction zones F_{reg} is proportional to the water content in the basalt layer f_{bas}, the mass fraction of water in the oceanic crust ϱ_{bas}, the thickness of oceanic crust d_{bas}, and the spreading rate S:

$$F_{reg} = f_{bas} \cdot \varrho_{bas} \cdot d_{bas} \cdot S \cdot R_{H_2O}, \tag{4}$$

where R_{H_2O} is the regassing ratio, representing the fraction of water that actually enters the deep mantle instead of returning to the surface through back-arc or andesitic volcanism.

The degassing and regassing of water representing the main volatile in our evolution model are presented in Fig. 1. For a detailed description of the model and the constants implemented see Franck and Bounama (1995b) and Franck (1998).

The balance equation for the mass of mantle water is given as:

$$\dot{M}_{mv} = F_{reg} - (\dot{M}_{mv})_d. \tag{5}$$

First we can solve Eqs. (3), (4) and (5) for the steady-state, i.e. the global volatile cycle proceeds in the same way, without any long-term evolutionary change. Balancing the degassing flux (3) with the regassing flux (4) gives

$$\varrho_{mv} \cdot d_m = f_{bas} \cdot \varrho_{bas} \cdot d_{bas} \cdot R_{H_2O}, \tag{6}$$

which can be used to estimate the steady state value of R_{H_2O}. Using the numerical values of $d_m = 56$ km (Langmuir et al., 1992), $\varrho_{mv} = 4.898$ kg/m^3 (present value for 3 ocean masses water in the mantle), $f_{bas} = 0.03$ (Schubert et al., 1989), $\varrho_{bas} = 2950$ kg/m^3 (Turcotte and Schubert, 1982), $d_{bas} = 5$ km (Schubert et al., 1989), we can find that the steady-state value for R_{H_2O} is 0.62.

The initial value of M_{mv} is the number n of ocean masses M_{ocean} originally present in the mantle:

$$M_{mv}\ (t = 0) = n \cdot M_{ocean}. \tag{7}$$

According to Ringwood (1975) the ratio of the water amount still remaining within the Earth to those in the atmosphere, hydrosphere, and sediments can be estimated between 3 and 20 (see also Jackson, 1998). In the sense of a conservative approximation we assume this ratio to be 3 for the present Earth, i.e. there are all together 4 ocean masses of water in the Earth system. No evidence exists so far about its distribution at the beginning of planetary evolution. Assuming that the total amount of water in the system is constant during Earth's history, we attempt to investigate different distributions of water at the beginning of planetary evolution ($t = 0$).

3. Calculation of volatile fluxes

The different fluxes of water at subduction zones as part of the general process of volatile exchange from Fig. 1 are shown in Fig. 2.

The regassing ratio R_{H_2O} as the fraction of subducting water that actually enters the deep mantle is defined as the ratio between regassing rate F_{reg} and subduction rate F_{sub}:

$$R_{H_2O} = \frac{F_{reg}}{F_{sub}}. \tag{8}$$

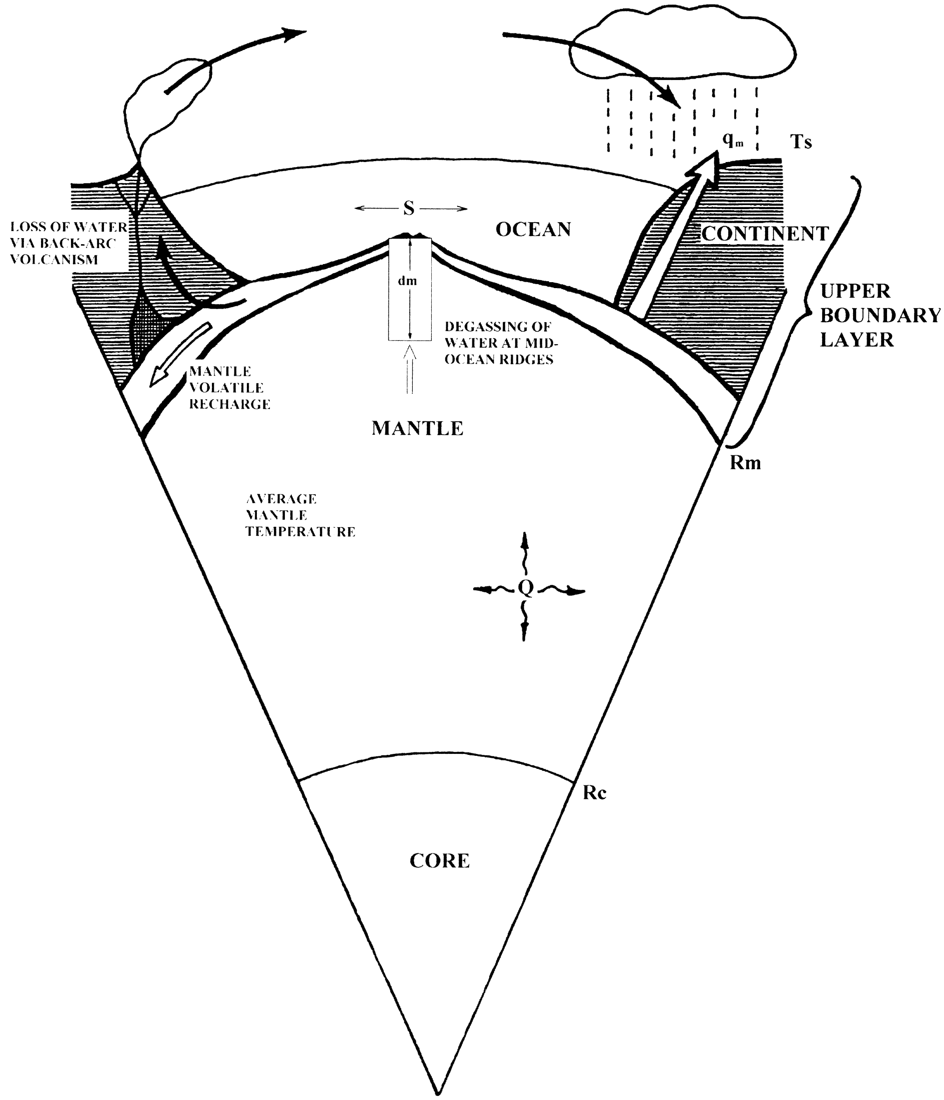

Fig. 1. Schematic view of the parameterized convection model with volatile exchange between mantle and surface reservoirs (not in scale). The heat flow q_m at the base of the lithosphere (upper boundary layer) results from cooling of the mantle with an average mantle temperature T_m and from a radiogenic energy production rate Q. The core radius, the mantle radius, and the surface temperature are R_c, R_m, and T_s, respectively. The mantle degasses at mid-ocean ridges from a partial melting depth d_m and an area defined by the areal spreading rate S. At subduction zones the volatiles are partly regassed to the mantle and partly recycled to the atmosphere via volcanism (see Franck, 1998).

The recycling ratio R_{rec} is the fraction of subducting water that returns to the surface in arc or andesitic magmas, i.e. the ratio between recycling flux F_{rec} and subduction flux F_{sub}:

$$R_{rec} = \frac{F_{rec}}{F_{sub}} = 1 - R_{H_2O}. \tag{9}$$

In order to check the influence of the continental growth model on the regassing ratio and the subduction flux we perform model runs with a delayed continental growth, a Condie (1990) model, a constant growth model, a Reymer and Schubert (1984) model, and a model with no continental growth (Franck, 1998; Franck et al., 2000). For the latter, the area of continents remains constant. Under the condition of 4 total ocean masses in the system and 1/3 distribution in the reservoirs surface/mantle both, the subduction flux and the regassing ratio differ slightly ($F_{\mathrm{sub}} = 1.015\ldots1.025\times10^{15}$ g/a, $R_{\mathrm{H_2O}} = 0.300\ldots0.320$). The continental growth model has no significant influence on the model results. Therefore, we choose the simple constant growth model for the following procedures.

Fig. 3 shows the result of the first numerical experiment with a total amount of 4 ocean masses water with different initial distributions in the reservoirs. To reproduce the contemporary situation of the water distribution (1/3) the regassing ratio $R_{\mathrm{H_2O}}$ was adjusted and fixed over the whole evolution time. The most important result is that $R_{\mathrm{H_2O}}$ changes only slightly despite the significantly different starting conditions (0/4, 1/3, 2/2, 3/1, 4/0). So $R_{\mathrm{H_2O}}\approx0.31$ is a good approximation for the regassing ratio of water deduced from our numerical experiment. Three curves with an initially "wet" mantle (0/4, 1/3, 2/2) show more or less a strong outgassing event at the beginning of planetary evolution followed by a subsiding process to end up in the recent situation of one ocean at the Earth's surface. Such an outgassing event in early Earth history is proved by geochemical data of noble gas depletion ratios (Staudacher and Allègre, 1982). Therefore, the model runs with an initially "dry" mantle (3/1, 4/0), which do not indicate this event, seem to be unlikely.

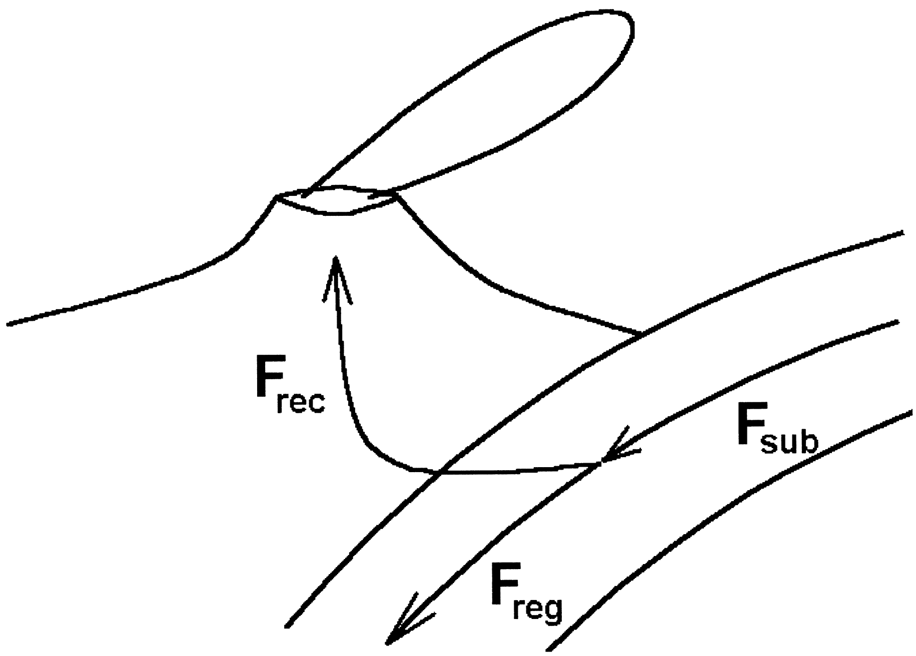

Fig. 2. Water fluxes at subduction zones: the subducting water flux F_{sub} is split into the regassing flux to the mantle F_{reg} and the recycling flux F_{rec} via back-arc or andesitic volcanism.

To demonstrate the influence of the regassing ratio on the water loss from the mantle we vary the value of R_{H_2O} for a fixed water distribution in the reservoirs (1/3). The results are shown in Fig. 4. As expected, $R_{H_2O}=0.3$ gives the right distribution of water in the reservoirs at present. In the case of smaller values ($R_{H_2O}=0.2$, 0.1) the recent water loss from the mantle is larger and reaches a value of one or two additional ocean masses at the surface, respectively. Note, that the model is based on the conservation of volatiles in the Earth's system. According to Ahrens (1990), large impacts of planetesimals at the end of Earth's accretion could have caused a loss of volatiles during the process of atmospheric blow-off and reduced the amount of surface water. Taking into account such processes, values of $R_{H_2O}<0.31$ could become realistic. In contrast, values of $R_{H_2O}>0.31$ give unrealistic results because in these cases the amount of water transported into the mantle leads to a surface reservoir which is far too small for reproducing the recent situation

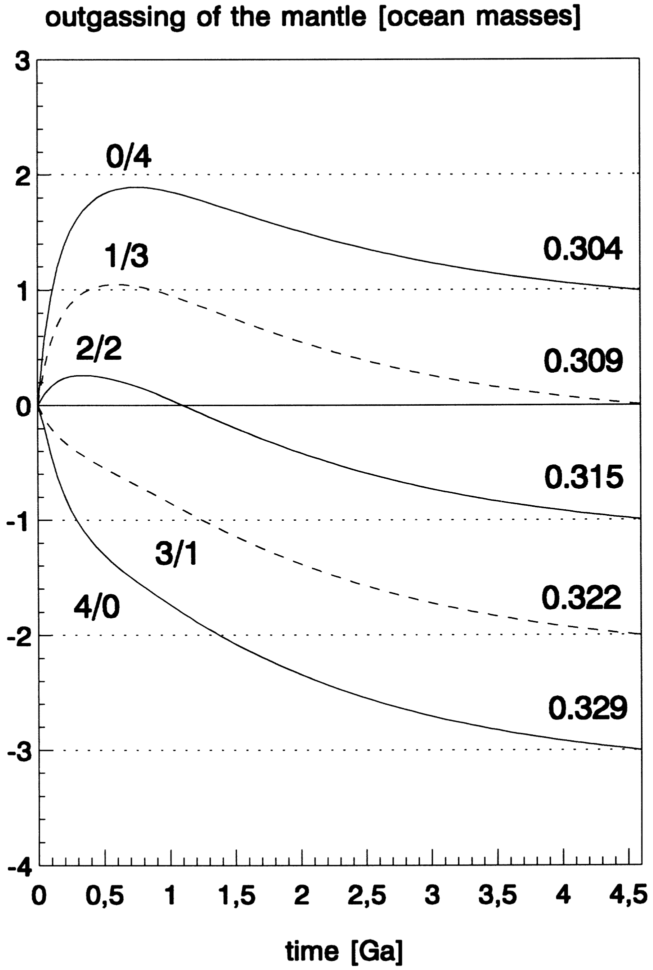

Fig. 3. Water loss scenarios for five different distributions of the amount of ocean masses between mantle and surface reservoirs at the beginning of planetary evolution (0/4, 1/3, 2/2, 3/1, 4/0). The regassing ratio R_{H_2O} was adjusted to end up with the present distribution (1/3) today ($t=4.6$ Ga).

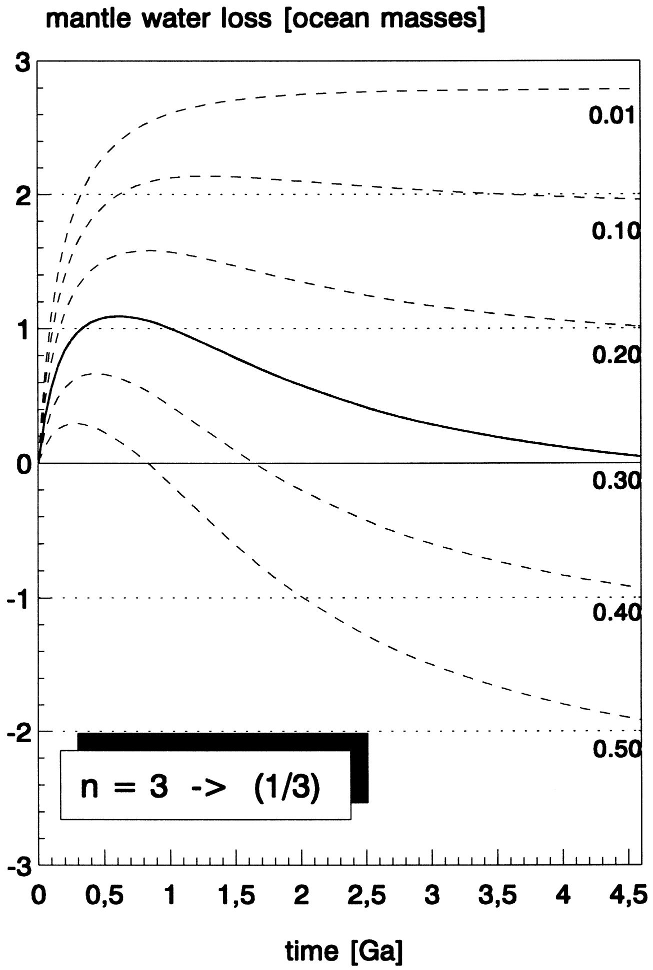

Fig. 4. Mantle water loss scenarios for different values of the constant regassing ratio R_{H_2O} and a fixed distribution at the beginning (1/3). Only the run with $R_{H_2O} = 0.3$ provides the exact distribution (1/3) for the present time. For $R_{H_2O} < 0.3$ we receive more water on the surface for the present time and for $R_{H_2O} > 0.3$ the surface reservoirs are depleted.

with or without an atmospheric blow-off. Therefore, $R_{H_2O} = 0.31$ corresponds to the upper bound for the regassing ratio resulting from our experiments.

The time series of the subduction, recycling, and regassing water fluxes during Earth's history for our "best-choice" conditions (1/3 and $R_{H_2O} = 0.31$) are shown in Fig. 5a. Keeping the regassing and the recycling ratio constant over Earth's history, the subduction flux and also the regassing and recycling fluxes declined about one order of magnitude since the Katarchaean.

In order to demonstrate the sensitivity of the regassing ratio to the total amount of water in the Earth system we run our model with 4–10 total ocean masses. The initial and recent distribution of water in the reservoirs is assumed to be equal, i.e. one ocean mass is located in the surface reservoir and the remaining water is located in the mantle. The results for the regassing ratio and

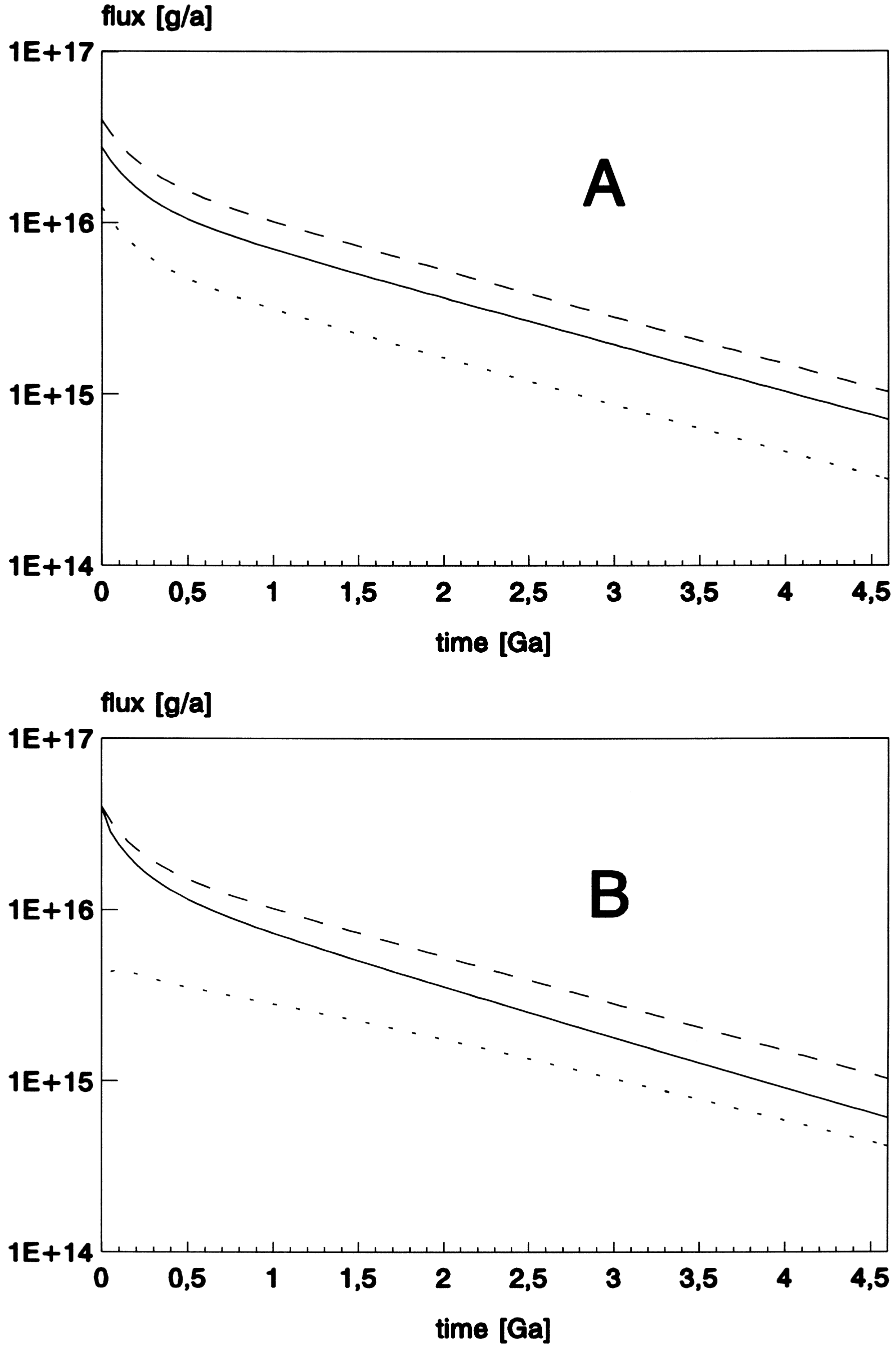

Fig. 5. Evolution of the subduction (dashed line), recycling (full line), and regassing (dotted line) fluxes of water during Earth's history for a initial water distribution of 1/3 and A: a constant regassing ratio $R_{H_2O} = 0.31$ and B: a time dependent regassing ratio [Eq. (9)]. In both cases the subduction flux declines about two orders of magnitude until present time.

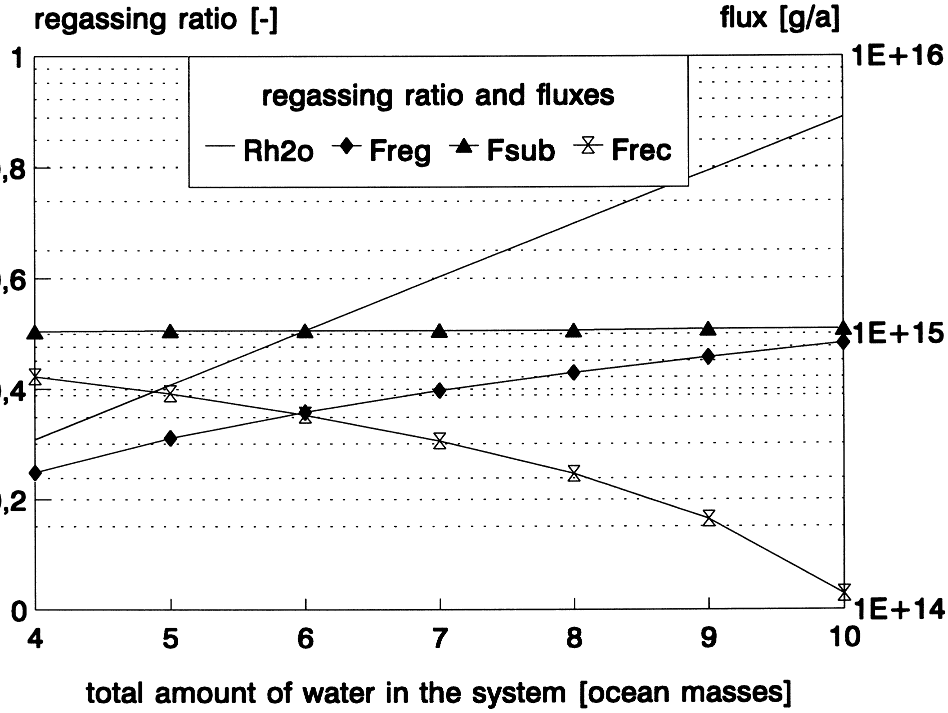

Fig. 6. Constant regassing ratio and modern fluxes under variation of the total amount of water in the system. There is no significant change of the subduction flux despite the different initial conditions while the constant regassing ratio changes rapidly.

the corresponding fluxes are plotted in Fig. 6. It is quite obvious that the subduction flux remains constant despite the variability of the total amount of water in the system while the regassing ratio differs from 0.31 to 0.89.

To check the influence of time dependence of the regassing ratio on the subduction zone fluxes we introduce a simple exponential time dependence of R_{H_2O}:

$$R_{H_2O}\ (t) = (m^{\bullet} t)^{1/4}\ + R_{H_2O}\ (0), \tag{10}$$

where m is adjusted to get the existing ocean on the Earth's surface and R_{H_2O} (0) is chosen to be 0.001, i.e. very small at the beginning of Earth's evolution. R_{H_2O} might have been even equal to zero in the Archaean when subducting slabs appear to have undergone partial melting.

In the case of total 4 ocean masses and 1/3 distribution m would have a value of 0.0059 to end up with a recent regassing ratio of 0.407. The model results for the loss of water from the mantle under the conditions of constant and time dependent regassing ratio are plotted in Fig. 7, the evolution of the fluxes is presented in Fig. 5b. As in the case of a time independent regassing ratio the subduction flux declined about one order of magnitude since the Katarchaean.

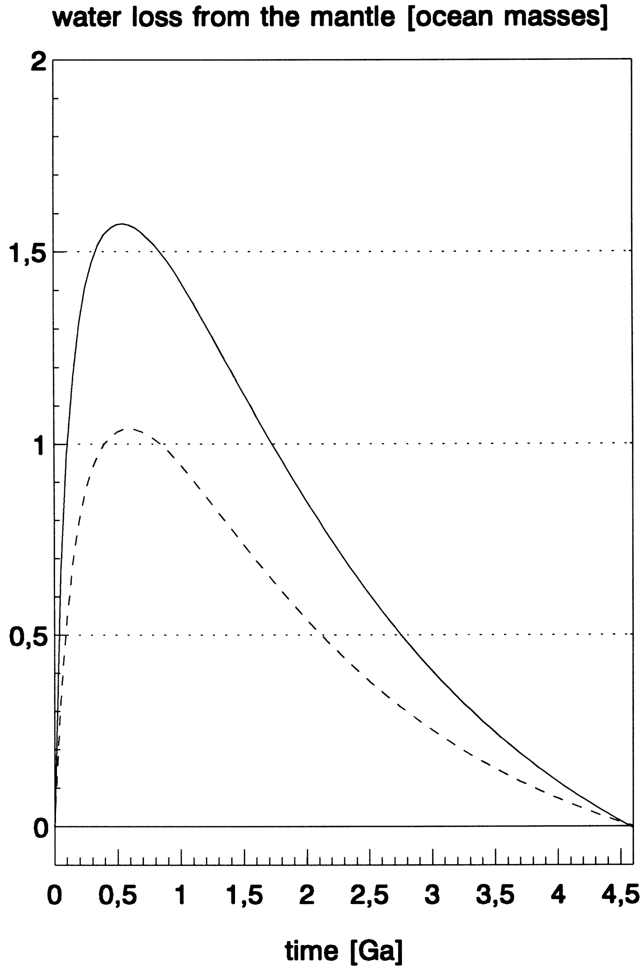

Fig. 7. Volatile loss from the mantle during Earth's evolution for model runs with a constant (dashed line) and a time dependent regassing ratio (full line) under the conditions of 4 total ocean masses in the system, initial reservoir distribution 1/3, and constant continental growth.

4. Discussion and conclusions

According to our estimations, the fraction of subducting water that actually enters the deep mantle (constant regassing ratio R_{H_2O}) is about 0.31. Values of $R_{H_2O} < 0.3$ are possible if the total amount of volatiles in the Earth system is not constant during Earth's evolution but decreases because for example, hydrogen escapes to space.

Compared to geochemical investigations, our chosen value for R_{H_2O} is smaller. Bebout (1996) found $R_{H_2O} = 0.85...0.95$. Ito et al. (1983) present a value for the recycling ratio $R_{rec} = 0.1$ that corresponds to $R_{H_2O} \approx 0.9$. There could be the following explanation for this discrepancy: at the beginning of the Earth's evolution both the subducting slabs and the mantle have been hotter than today. Under such conditions water was being released from the slabs easily and the recycling ratio was larger while the regassing ratio was smaller, compared to today's ones. In our model these ratios stay constant over the whole history of Earth. Therefore, $R_{H_2O}=0.3$ (or $R_{rec}=0.7$) are only average values and the present values for R_{H_2O} and R_{rec} are larger and smaller, respectively. The steady-state value of $R_{H_2O}=0.62$ is a value between the results from geochemical investigations and our preferred average value over the whole Earth's history.

To represent a variety of complex processes geochemists consider the apparent water return of only 5–15% of the subduction flux via arc volcanism. Not all of the remaining 85–95% H_2O is necessarily deeply regassed (subducted), most of it is likely to be lost in forearcs due to devolatilization reactions. This fluid then ascends into the forearc mantle wedge (hydrating it) or moves toward the oceans along fault structures. From a geochemical point of view, it is impossible to come up with the percentage of initially subducted water, which is returned to the deep mantle because it is unknown how much of the non-returning 85–95% H_2O is actually reversed toward the surface/oceans. First assessments give values of the regassing ratio that are even smaller than 30% (Bebout, personal communication). This means that, of the initially subducted water inventory, 5–15% are returned in arcs (recycled), 30% or less are returned to the deep mantle (regassed), and 55–65% or more are going toward the surface after being released by devolatilization. Following this argumentation, our value of the regassing ratio of about 0.3 is quite reasonable.

To check the assumption that a time dependent regassing ratio would give higher modern values we consider a simple exponential increase with time. The result is a significantly increased value of R_{H_2O} (from 0.309 to 0.407). For an unlikely linear dependence of R_{H_2O} on time this increase of the modern regassing ratio is even more drastic (up to 0.74). Fig. 7 shows a much stronger outgassing event at the beginning of Earth's evolution if time dependence of the regassing ratio is accepted. If a plausible time evolution of the regassing ratio is unknown, a detailed assessment of the recent value from the geophysical modelling approach is highly uncertain. Nevertheless, compared to the geochemical investigations our calculations suggest a smaller value of the modern regassing ratio of about 0.3–0.4.

Here we present our values for the modern fluxes of H_2O derived from a thermal evolution model with constant continental growth under the conditions of 4 ocean masses present in the system with an initial distribution in the reservoirs surface/mantle of 1/3, and a time independent regassing ratio:

$$F_{sub} = 1.01\times10^{15}\ \text{g/a},$$

$$F_{reg} = 3.14\times10^{14}\ \text{g/a},$$

$$F_{rec} = 7.01\times10^{14}\ \text{g/a}.$$

The value of the subduction flux is in good agreement with data given by Rea and Ruff (1996), $F_{sub}=0.9\times10^{15}$ g/a, Bebout (1996), $F_{sub}=0.9\ldots1.9\times10^{15}$ g/a, Javoy (1998), $F_{sub}=1\times10^{15}$ g/a, and Hadfield (1999), $F_{sub}=1.12\times10^{15}$ g/a. Also the regassing flux is in the same order of magnitude as given by Javoy (1997, 1998), $F_{reg}=1\times10^{14}$ g/a. Therefore, our results for the subduction zone fluxes are likely to represent the modern situation. Also the decline in the subduction water flux (and the regassing and recycling fluxes as well) by about one order of magnitude since the

Katarchaean is a reasonable result. In general, our results imply that the present global water cycle is not in the steady state. In this way the cycling process as a feature of structure formation in the Earth system is mainly influenced by an evolutionary process, namely the cooling in the Earth's interior.

A further interesting point concerns the influence of the continental growth on the volatile exchange in the Earth's history and even in the planetary future. According to Franck and Bounama (1997), the continental growth model has no essential influence on the thermal history of the Earth, but has a stronger influence on the volatile exchange. Such an interplay between the influence of temperature and volatiles on the viscosity was already observed by McGovern and Schubert (1989). In their scenarios they found that the rate of change of the temperature tends to the same value for the volatile-dependent and volatile-independent rheologies. In all numerical simulations with a high initial average mantle temperature water is outgassed relatively rapidly, which agrees with noble gas depletion ratios found in mid-ocean ridge basalt and in the atmosphere (Staudacher and Allègre, 1982). In the delayed and constant continental growth model there is the most rapid early outgassing event, and the largest amount of water is exchanged with surface reservoirs. This seems to be in best agreement with the noble gas depletion ratios mentioned above. In all three models the early outgassing event could be accompanied by hot-spot volcanism, which has not yet been included in this model.

If we consider the water loss from the mantle as shown for example in Fig. 7, we always find the very early outgassing event, already discussed above, followed by a more or less moderate decrease in mantle water loss. Extrapolating our results into the future, we find negative water loss from the mantle, i.e. our planet will lose water from the surface reservoirs to the mantle. So we are concerned with one of the main questions in Earth's sciences: how much water will be available in surface reservoirs in the future? Could all the surface reservoirs disappear as a result of subduction processes or/and as a result of a runaway greenhouse effect caused by increasing solar luminosity? Such questions will be investigated in a succeeding paper (Bounama et al., 2001).

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