



Subduction and atmospheric escape of Earth's seawater constrained by hydrogen isotopes



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ARTICLE INFO

Article history:

Received 28 March 2018

Accepted 10 June 2018

Available online xxxx

Editor: B. Buffett

Keywords:

global water cycle

hydrogen isotopes

subduction

atmospheric escape

early Earth

seawater

ABSTRACT

The hydrogen isotopic (D/H) ratio reflects the global cycling and evolution of water on Earth as it fractionates through planetary processes. We model the water cycle taking seafloor hydrothermal alteration, chemical alteration of continental crust, slab subduction, hydrogen escape from the early Earth, and degassing at mid-ocean ridges, hot spots, and arcs into account. The differences in D/H ratios between present-day oceans, oceanic and continental crust, and mantle are thought to reflect isotopic fractionation through seafloor alteration, chemical alteration, and slab dehydration. However, if the speed of plate tectonics has been nearly constant throughout Earth's history, the degassing and regassing rates are too small to reach the present-day D/H ratios. We show that (a) hydrogen escape from reduced early atmosphere, (b) secular net regassing, or (c) faster plate tectonics on early Earth is needed to reproduce the present-day D/H ratios of the water reservoirs. The low D/H ratio of Archean seawater at 3.8 Ga has previously been interpreted as a signature of (a) hydrogen escape, but we find it can also be explained either by (b) secular net degassing or by (c) faster plate tectonics on early Earth. The rates of hydrogen escape from early Earth and secular regassing on present-day Earth are constrained to be lower than 2.1×10^{11} kg/yr and 3.9×10^{11} kg/yr. Consequently, the volume of water in the present-day mantle could result entirely from the regassing through Earth's history. In that case, the volume of initial oceans could be 2 to 3 times larger than that of current Earth. We suggest that, in addition to the D/H ratio of Archean seawater, identifying the D/H ratios of both seawater and mantle throughout Earth's history would allow to distinguish these evolutionary scenarios.

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1. Introduction

Water plays a critical role in controlling the physical and chemical evolution on Earth through atmosphere–ocean–continent interactions which control the atmospheric composition, the climate through the carbon cycle, the subduction of water, and possibly even the emergence and evolution of life (e.g., Gaillard et al., 2011; Walker, 1977; Höning et al., 2014; Höning and Spohn, 2016; Dohm and Maruyama, 2015). Furthermore, the abundance of water in Earth's interior influences the mantle melting, rheology, and style of convection (e.g., Hirschmann, 2006; Karato and Jung, 2003; Mei and Kohlstedt, 2000).

The abundance of water on the surface and in the interior is controlled by the deep water cycle between the oceans and mantle, and loss caused by hydrogen escape throughout Earth's history. Slab subduction transports water as bound and pore water in metamorphic rocks and sediments that originate from hydrother-

mal alteration of the seafloor and chemical alteration of continental crust (e.g., Jarrard, 2003; Bodnar et al., 2013; Höning et al., 2014; Höning and Spohn, 2016). While the majority of the subducted water returns to the oceans directly by updip transport and indirectly by arc volcanism, some trace amounts of water may remain in the mantle. Water can return from the mantle to the exosphere (here defined as the atmosphere and hydrosphere) by degassing at mid-ocean ridges and ocean islands. Although the photolysis of water has a negligible effect on the loss of hydrogen from the atmosphere today, the hydrogen escape through the photolysis of methane in the reduced early atmosphere before the great oxidation event (GOE) at 2.5 Ga could have a more significant impact (Catling et al., 2001).

Despite its importance to control the water budget, the balance between the degassing and regassing as well as the early hydrogen escape flux is poorly understood. We note that the term “regassing” means the water transport to the mantle as bound and pore water in metamorphic rocks and sediments. Net regassing from the oceans to the mantle has been suggested from the geochemical estimates (Ito et al., 1983). The continental freeboard is

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proposed to be nearly constant from the end of the Archean (e.g., Schubert and Reyrer, 1985) and is interpreted as the degassing and regassing rates almost achieving balance (e.g., Lécuyer et al., 1998; Parai and Mukhopadhyay, 2012). However, Korenaga et al. (2017) recently argued that the relative buoyancy of continental lithosphere with respect to oceanic lithosphere was higher in the past, which requires a larger volume of oceanic water at the time to keep continental freeboard constant. Hydrogen escape on early Earth is even more poorly constrained as the atmospheric composition at that time is not well known.

Hydrogen isotope (D/H) ratio has been used to constrain the global cycle and loss of water on Earth, as it fractionates through planetary processes. Earth's mantle is known to have $\delta D = -80\%$ to -60% ($\delta D = [(D/H)_{\text{sample}}/(D/H)_{\text{reference}} - 1] \times 10^3$, where the reference is the standard mean ocean water, hereafter SMOW), which is lower than that of today's oceans (defined here as the total hydrosphere) (Kyser and O'Neil, 1984; Clog et al., 2013). The low mantle δD value has been considered to suggest that the mantle became isolated from the oceans through geologic time (Kyser and O'Neil, 1984), or that water in the mantle has been isotopically fractionated from the source seawater because of seafloor alteration and slab dehydration processes (Lécuyer et al., 1998; Shaw et al., 2008, 2012). Isotopic analysis of Archean minerals and rocks has found that Archean seawater has a δD value lower than that of present-day oceans, which has been interpreted as a signature of water loss caused by the hydrogen escape (Hren et al., 2009; Pope et al., 2012).

While D/H ratio has been widely utilized to constrain those processes of the water cycle and loss, there is no comprehensive model of the D/H evolution which involves all relevant processes. Previous studies considered the degassing and regassing (Lécuyer et al., 1998; Shaw et al., 2008) or the hydrogen escape (Pope et al., 2012) only. In addition, the D/H ratios of the mantle and Archean seawater have been considered separately to constrain these different processes. Because all water reservoirs are coupled to each other, all these processes and D/H constraints should be considered simultaneously, which is the aim of this study.

We model the global water cycle taking seafloor hydrothermal alteration, chemical alteration of continental crust, slab subduction, atmospheric escape, and degassing at mid-ocean ridges, hot spots, and arcs into account. The model calculations are compared with the D/H ratios of water in different reservoirs on present-day Earth and of Archean seawater to constrain the rates of hydrogen escape from early Earth and of secular regassing on present-day Earth. Section 2 presents the model. Section 3 shows the results. The implications for the evolution of water on Earth are discussed in Section 4. We conclude in Section 5.

2. Methods

2.1. Model

We constructed a global water cycle model taking the D/H compositions into account. Four reservoirs were considered in our model: the oceans, continental crust, oceanic crust, and mantle. These reservoirs exchange water through seafloor hydrothermal alteration, chemical alteration of continents, slab subduction, and degassing at mid-ocean ridges, hot spots, and arcs (Fig. 1). Hydrogen loss to space induced by photolysis of methane was considered to have occurred on early Earth before the GOE at 2.5 Ga. The oceans in our model include water in small reservoirs that exchange water with oceans over short timescales: atmosphere, biosphere, surface water, ground water, and glaciers/polar ice, see Table 2. Hereafter the oceans with the small reservoirs are referred to as “bulk oceans” when we would like to distinguish them from seawater without small reservoirs. Exploring the possible ranges of

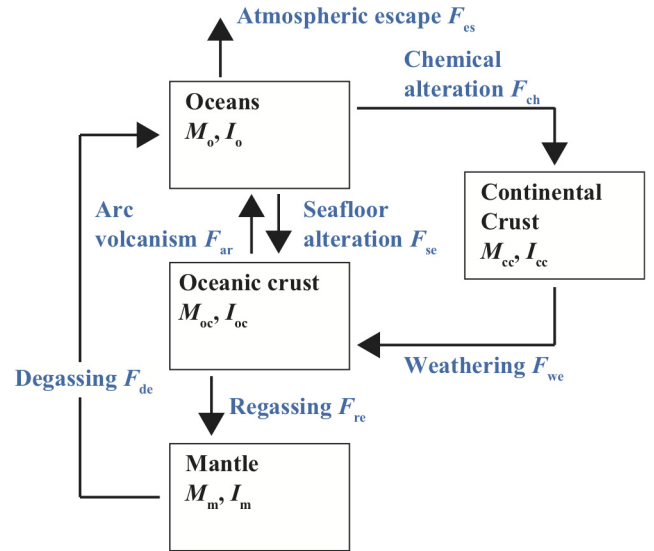


Fig. 1. Schematic view of Earth's water cycle in our model.

fluxes, we constrain the water cycle and discuss the implications for the evolution of water on Earth.

Evolution of the masses and D/H ratios of water in each reservoir was calculated by using the following equations,

$$\frac{dM_i}{dt} = \sum_{\text{sources}} F_k - \sum_{\text{sinks}} F_k \quad (1)$$

$$\frac{d}{dt}(M_i I_i) = \sum_{\text{sources}} F_k f_k I_{i'} - \sum_{\text{sinks}} F_k f_k I_i \quad (2)$$

$$\frac{f_{re}}{f_{ar}} = f_{dehy} \quad (3)$$

$$\frac{F_{ar}}{F_{ar} + F_{re}} f_{ar} + \frac{F_{re}}{F_{ar} + F_{re}} f_{re} = 1 \quad (4)$$

where M_i and I_i are the mass and D/H ratio of water in the reservoir i , and F_k and f_k are the flux of the process k and its fractionation factor. The sources and sinks for each reservoir are described in Fig. 1. Hereafter subscripts $i = o, cc, oc, \text{ and } m$ denote the oceans, continental crust, oceanic crust, and mantle, respectively. The subscript i' in Equation (2) denotes a reservoir other than i . Subscripts $k = ch, ar, se, de, es, we, \text{ and } re$ denote the chemical alteration, arc volcanism, seafloor alteration, degassing, atmospheric escape, weathering, and regassing, respectively. Equations (3) and (4) give f_{ar} and f_{de} by considering the dehydration-induced fractionation and mass balance. Assuming $d/dt = 0$ in Equation (2) gives a steady state in D/H, which is useful to understand the numerical results (Appendix A).

Our model assumed that the fluxes depend on the masses of water in the reservoirs and time as follows:

$$F_{ch} = F_{ch}^0 \frac{A_c(t)}{A_c^0} \quad (5)$$

$$F_{se} = F_{se}^0 \times f(t) \quad (6)$$

$$F_{ar} = F_{ar}^0 \frac{M_{oc}(t)}{M_{oc}^0} \times f(t) \quad (7)$$

$$F_{de} = F_{de}^0 \frac{M_m(t)}{M_m^0} \times f(t)^{\frac{1}{2}} \quad (8)$$

$$F_{we} = F_{we}^0 \frac{M_{cc}(t)}{M_{cc}^0} \quad (9)$$

$$F_{re} = F_{re}^0 \frac{M_{oc}(t)}{M_{oc}^0} \times f(t) \quad (10)$$

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