Surface exposure constraints on the mantle water budget

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ABSTRACT

Mantle water content estimates range from 0.5 - 15 oceans of water. Its evolution is even more unclear. Rapid degassing during mantle solidification likely released much of the water to the surface, initially flooding the Earth. However, evidence for sub-aerial land from at least 3.5 Ga means that much of this water must have been rapidly cycled back into the mantle. We use a parametrised convection model and hypsometric curve to assess how much water can be taken into the mantle and still satisfy evidence for sub-aerial land. Even if only the highest peaks are exposed, the initial ocean must have been less than 1.5 current oceans to explain subaerial exposure throughout most of Earth history. Today, this implies any water in the mantle >0.5 oceans subducted to the interior must be primordial and isolated from the convecting mantle for most of Earth's history.

INTRODUCTION

The one thing that is certain about water in the Earth is that there is 1 ocean's worth at the surface now. It is also becoming clear that at least 5 oceans of water are in the core (Li *et al.*, 2020). But estimates for the current mantle water content vary widely, from ~0.5 oceans (Smyth and Jacobsen, 2013) up to 15 oceans (Marty, 2012). Shortly after Earth's formation, most water remaining in the magma ocean after core formation would be released to the surface during mantle solidification (Tikoo and Elkins-Tanton, 2017), forming the early ocean. How much water the early ocean contained, how the ocean volume and fraction of exposed land has evolved, and how that relates to the water budget of the mantle is not clear.

Zircon inclusions show that water has been interacting with the crust since 4.3 Ga (Mojzsis et al., 2001). Examination of strontium isotopes suggests surface exposure may have been as much as 12% ~3.7 Ga (Roerdink et al., 2022). By the late Archean, estimates have a wide range. Some suggest more water at the surface than the present day (Pope et al., 2012; Höning and Spohn, 2016; Dong et al., 2021). The prevalence of submarine continental flood basalts during this time may indicate the surface was flooded, with less than 4% exposed above the ocean (Flament et al., 2013). In contrast, widespread subaerial weathering and hence exposure are supported by evidence from paleosols suggesting global exposure of continents during from 3.7-3.2 Ga (Luskin et al., 2019; Retallack and Noffke, 2019). Oxygen isotope analyses suggest that by the end of the Archean, the surface exposed cannot have been too far off what it is at the present day (Bindeman et al., 2018) and to explain sulphur isotopes in the sedimentary record, large areas of the surface needed to be exposed by the end of the Archean (Ohmoto, 2020). See Appendix 1 for more detail.

Surface exposure is also controlled by the Earth's average topography or the hypsometry. Ocean basins may have been shallower in the past due to higher mantle temperatures and buoyant oceanic crust (Flament *et al.*, 2008), whilst the timing of continental growth is still under discussion. Some favour rapid and early growth (e.g. Guo and Korenaga, 2020) corresponding to

~20% exposure ~4.2 Ga (Korenaga, 2021) whereas others favour gradual growth implying later exposure (e.g. McLennan and Taylor, 1982). Continental freeboard, the average height of continents above sea level, is thought to have remained constant since 2.5 Ga and due to the lack of evidence for ocean mass over time, isostatic models generally treat the ocean mass as a constant (Kasting and Holm, 1992), with a few exceptions (Flament et al., 2008; Korenaga et al., 2017).

We take a different approach and model the deep-water cycle (Fig. 1A) to determine the evolution of the surface reservoir mass (Chotalia et al., 2020). By considering different initial amounts of water on the surface (5 or 1.5 oceans), we show that hypsometry and subaerial exposure puts very strong constraints on the amount of water that can be lost to the mantle. This limits both the size of the surface ocean and the amount of recycled water in the mantle. We argue that no more than 0.5 oceans of water can be returned to the mantle over the age of the Earth. Any more water must be primordial and isolated from the convecting mantle supplying mid-ocean ridges (MORs).

METHODS

To investigate sub-aerial constraints on deep water transport through time, we consider the degassing of only MORs (D) and regassing at subduction zones (R) in a parametrised convection model (Appendix 2). Regassing and degassing are both dependent on the plate velocity, which is controlled by the convective vigor of the mantle. As Earth cools, changes in mantle temperature (Fig. A1a) decrease the convective vigor and plate velocity (Fig. A1b), affecting D and R. These models are often used due to their light computational load and ability to capture first order controls on planetary evolution, allowing large swathes of the parameter space to be examined (e.g. Sandu et al., 2011; Chotalia et al., 2020). We constrain viscosity and hence convective vigor by limiting plate velocity to <10 cm/yr over the last 2.5 Ga (Stixrude and Lithgow-Bertelloni, 2012, Appendix 4) and allow 400 K cooling (Höning and Spohn, 2016) to prevent thermal catastrophe and a molten mantle. We sweep through combinations of average degassing and regassing efficiency (F_D and F_R) from 0 (no D or R) to 1 (maximum possible D and R), using the present-day degassing rate to constrain the acceptable models (Table A1) and test the model sensitivity to the efficiency of the water cycle. We track mass changes in water for the mantle interior (Fig. 1B and 1C) and surface with time, converting them to sea level using the present-day hypsometric curve (Fig. 2 and Appendix 3). As evidence suggests exposure comparable to the present day might be possible from the late Hadean (Korenaga, 2021) into the Proterozoic (Windley, 1977), we only accept models that have the present day exposure today and consider present day exposure at the end of the Archean to see which range of scenarios are acceptable. This is conservative given the range when present day exposure may occur and the likely limited relief in the Archean. We show that considering the evidence of early sub-aerial interaction greatly limits the contribution of surface water to the mantle interior.

Deleted: at the end of the Archean

RESULTS

Figs. 1B and 1C show the present-day water content of the mantle together with the final degassing fluxes from parametrised model runs. Results are given for two end member cases: Fig. 1B begins with 5 oceans and Fig. 1C with 1.5 oceans. Also shown is the current degassing rate, 10^{10} - 10^{11} kg/yr (shaded region). In Fig. 1B, it is possible to subduct 4 oceans of water in 4.6 Ga for a range of F_D and F_R values represented by the solid red contour. This range becomes more restricted if we only consider cases that satisfy the present-day D, but nevertheless, it is possible to meet these conditions. Where we start with just 1.5 oceans of water at the surface (Fig. 1C), it is also possible to match current ocean mass and current D with a wider range of F_D and F_R.

These results show that Earth can permanently remove large amounts of water from the surface into the mantle, matching present ocean mass and present degassing. However, these scenarios have considerable implications for past sea level. Fig. 2B shows the evolution of sea level predicted by the parametrised convection models; both models end with 1 ocean at the surface after 4.6 Ga (solid, red). Starting with 5 oceans, sea level is 11 km and decreases with time. However, the oceans would still cover all land after 1 Gyr, only exposing 0.4% of the present topography after 2.5 Ga (Table 1, Fig. 2C). This is counter to evidence that some land is exposed after 3.6 Ga. Even for models that begin with even just half an ocean extra at the surface (Fig. 1C and 2B), only 6-10% of present-day topography would be exposed at the end of the Archean, against our condition for exposure comparable to the present day at this time (Bindeman et al., 2018).

Since it is impossible to permanently remove 4 oceans of water into the mantle over 4.6 Ga without having the Earth flooded over most of its history, we now consider if it is possible to satisfy the observation of abundant sub-aerial land by 2.5 Ga. Figs. 1B and 1C shows the values of F_D and F_R which result in 1 ocean remaining at the surface after 2.5 Ga (dashed, red). However, the required F_R is now so high that no water remains at the surface by the present day. The evolution of sea level for those cases is shown in Fig. 2B (dashed, red). For the case starting with 5 oceans, sea level decreases rapidly. This efficient subduction of water continues after 2.5 Ga subducting the water to the mantle, drying the surface. In other words, we can either subduct large amounts of water over Earth's history but have no appreciable sub-aerial land until recently or subduct it quickly but totally desiccates the surface. Neither model is acceptable. Even for the case where the surface has just half an extra ocean, we can either have abundant sub-aerial land after 2.5 Ga and a very small modern ocean, or very little land at 2.5 Ga and an oceans worth at the surface now.

We can consider another case where water is quickly transported to the mantle until it becomes saturated. Once saturated, there would be a steady state between water recycled into the mantle at subduction zones and degassed at MORs, keeping ocean mass and sea level constant. Fig. 2B shows the case beginning with 5 oceans, where 4 oceans are subducted before 2.5 Ga, saturating the mantle. Nominally, this situation can satisfy the observation of 1 ocean at the surface and abundant sub-aerial land after 2.5 Ga. However, the degassing rates predicted for the present day are unreasonably high at ~10^{12} kg/yr (Fig. 3). Even if mantle saturation was only half an ocean of water, far less than mineral physics estimates (Dong et al., 2021) current degassing would still be greater than observed now, making mantle saturation another unlikely option. Hence, to remove excess surface oceans in the first few billion years, efficient regassing early on in Earth's history followed by a change in efficiency would be required for any water to remain at the surface today. We know of no mechanism for such a decrease in efficiency, and is in contrast to evidence that regassing becomes more efficient towards the present day (Parai and Mukhopadhyay, 2018). We conclude, therefore, that to maintain surface exposure throughout most of Earth history and to match present day degassing rates, the 1.5 initial oceans end member is the more likely of the two and multiple oceans have not been lost to the mantle interior.

DISCUSSION AND CONCLUSION

Assumptions

The above analysis contains some assumptions. We have used a current day hypsometry curve to estimate the amount of land above sea level but during the Archean, ocean basins are expected to be shallower and continental highs lower due to a hotter mantle (Flament et al., 2008). Even half an extra ocean could easily submerge all continents (Fig. A2, Appendix 5). This work is at the limit of what can be achieved with parametrised models (Appendix 4) and further work that includes continental crust growth, ocean mass evolution and the resulting isostasy would be required to rigorously calculate how exposure evolves. However, our current understanding of the effects of these characteristics all reinforce our main conclusion that only 0.5 oceans can be lost to the interior, while still satisfying surface geological constraints.

Our modelling is also based on present-day subduction mechanisms, which may not be appropriate prior to 3.6 Ga. Studies have shown effective recycling via the heat pipe mechanism (Moore, 2008), drip subduction (Lourenço et al., 2018) and episodic subduction (Sleep et al., 2014). However, during multiple episodes of melting and recycling, heating and dehydration would release water towards the surface (Cerpa et al., 2022). Surface water would be confined to the top of the mantle without pervasively hydrating the deeper mantle. These mechanisms would simply delay when the surface is able to hydrate the mantle via subduction, reducing the amount of water the surface can contribute to the mantle budget, further reinforcing our conclusion.

Implications for Mantle Water Content

We suggest that any water in the mantle exceeding 0.5 oceans (likely less) must be primordial and has existed since the magma ocean solidification. This is in agreement with the requirement for a primitively hydrated mantle source for the formation of the earliest continental-like crust (Smithies et al., 2021). Hiding significant amounts of water during accretion, solidification and subsequent convection is, however, difficult. Models of upward crystallization concentrate water in the near surface (Tikoo and Elkins-Tanton, 2017), while considering the rheological transition as the mantle solidifies suggests 99% of water is trapped until degassed at MORs in the late Hadean to the early Archean (Miyazaki and Korenaga, 2022).

Crystallization from the middle of the magma ocean can isolate dense volatile enriched melts in the deepest mantle (Labrosse et al., 2007). Large Low Shear Velocity Provinces (LLSVPs) and Ultra Low Velocity Zones (ULVZs) may be the solution but their size presents limitations. ULVZs are too small to host significant amounts of water. In the LLSVPs, even 1 ocean would be equivalent to ~3800 ppm, compared with 1000 ppm found in ocean island basalts (Marty, 2012). Whether such wet LLSVPs would be resistant to melting and convective mixing is an open question. Similarly, a wet transition zone with 3 oceans of water (~10,000 ppm; Pearson et al., 2014) would need to have remained hydrated for 4.5 Ga, or gradually hydrated from another mantle source. However, recent models show that large differences in water content between the transition zone, upper and lower mantle cannot be maintained over billions of years (Drewitt et al., 2022).

Regardless of continuing discussions on the evolution of water capacity and water transport, consideration of subaerial exposure when examining the water cycle greatly limits the contribution of the surface to the mantle water budget and is likely less than 0.5 oceans. This implies any estimates of mantle water budget exceeding this must be primordial and hidden from the convective mantle.

FIGURE AND TABLE CAPTIONS

Figure 1. (A) Reservoirs and fluxes of the deep water cycle, water contents of MORBs, OIBs (Hirschmann, 2006) and hydrous diamond inclusion sources (Pearson et al., 2014). Degassing of the mantle at the MORs (D) releases water to the surface whilst regassing (R) at subduction zones brings water into the mantle. (B) and (C) are contour maps of mantle water content at the present day from parameterised convection models run with different degassing and regassing efficiencies, F_D and F_R. All water starts on the surface with (B) 5 or (C) 1.5 oceans of water. The solid red line shows values of F_D and F_R required to subduct excess oceans, leaving 1 ocean at the surface by the present day. Grey dashed-dotted lines indicate the present-day D and the shaded region shows cases which match D for the present-day. Models which match the present-day conditions are when the present day contour and shaded region overlap. F_D and F_R values resulting in 1 ocean at the surface by 2.5 Ga contour (dashed) lie above the present day contour, indicating the present-day condition of 1 ocean at the surface is not met.

Figure 2. (A) Present-day hypsometry (Korenaga et al., 2017) with illustrative sea levels shows even small changes in ocean mass cover most of the land. (B) Relative sea level and (C) surface exposure evolution through time for cases beginning with 5 and 1.5 oceans at the surface (Table 1). The insets show the ocean mass-sea level and ocean mass-surface exposure relationship, calculated by integrating between various sea levels and present-day hypsometry. Solid red lines show sea level for the two cases which result in 1 ocean worth of water at the surface after 4.6 Ga. Starting with 5 oceans uncovers, at most, a few percent of topography between 3.5 and 2.5 Ga. Even starting with only 1.5 oceans only uncovers 10% of land, not enough to meet our end member surface exposure condition comparable to the present. The dashed red lines show the evolution of sea level for models that subduct excess oceans by 2.5 Ga. Starting with 5 oceans,

the regassing rate is so high that all water is subducted into the mantle, drying out the surface. Starting with just 1.5 oceans at the surface results in oceans ~1.5 km shallower than today, exposing most of the continental shelf. If the mantle becomes saturated at 2.5 Ga (schematic - dashed, purple), any excess water introduced into the mantle would be degassed and the mass in both reservoirs would remain constant after 2.5 Ga.

Figure 3. Degassing (dashed-dotted) and regassing fluxes (solid), from cases in Fig. 2B that subduct excess oceans by 2.5 Ga. Regassing flux is always higher than degassing flux, such that the excess oceans are subducted by 2.5 Ga. However, if by 2.5 Ga the mantle is saturated, regassing at this high rate continues and degassing must increase to keep the surface ocean mass and hence sea level stable (purple, schematic). This increases degassing flux to values up to an order of magnitude higher than is expected for the present-day (shaded region).

Table 1. Parameters for the parametrised convection model results in Fig. 2B

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REFERENCES CITED

Bindeman, I.N., Zakharov, D.O., Palandri, J., Greber, N.D., Dauphas, N., Retallack, G.J., Hofmann, A., Lackey, J.S., and Bekker, A., 2018, Rapid emergence of subaerial landmasses and onset of a modern hydrologic cycle 2.5 billion years ago: Nature, v. 557, p. 545–548, doi:10.1038/s41586-018-0131-1.

Cerpa, N.G., Arcay, D., and Padrón-Navarta, J.A., 2022, Sea-level stability over geological time owing to limited deep subduction of hydrated mantle: Nature Geoscience, v. 15, p. 423–428, doi:10.1038/s41561-022-00924-3.

Chotalia, K., Cagney, N., Lithgow-Bertelloni, C., and Brodholt, J., 2020, The coupled effects of mantle mixing and a water-dependent viscosity on the surface ocean: Earth and Planetary Science Letters, v. 530, p. 115881, doi:10.1016/j.epsl.2019.115881.

Dong, J., Fischer, R.A., Stixrude, L.P., and Lithgow-Bertelloni, C.R., 2021, Constraining the Volume of Earth's Early Oceans With a Temperature-Dependent Mantle Water Storage Capacity Model: AGU Advances, v. 2, doi:10.1029/2020av000323.

Drewitt, J.W.E., Walter, M.J., Brodholt, J.P., Muir, J.M.R., and Lord, O.T., 2022, Hydrous silicate melts and the deep mantle H2O cycle: Earth and Planetary Science Letters, v. 581, p. 117408, doi:10.1016/j.epsl.2022.117408.

Flament, N., Coltice, N., and Rey, P.F., 2008, A case for late-Archaean continental emergence from thermal evolution models and hypsometry: Earth and Planetary Science Letters, v. 275, p. 326–336, doi:10.1016/j.epsl.2008.08.029.

Flament, N., Coltice, N., and Rey, P.F., 2013, The evolution of the 87sr/86sr of marine carbonates does not constrain continental growth: Precambrian Research, v. 229, p. 177–188, doi:10.1016/j.precamres.2011.10.009.

Guo, M., and Korenaga, J., 2020, Argon constraints on the early growth of felsic continental crust: Science advances, p. 1–11, doi:10.1126/sciadv.aaz6234.

Hirschmann, M.M., 2006, WATER, MELTING, AND THE DEEP EARTH H 2 O CYCLE: Annual Review of Earth and Planetary Sciences, v. 34, p. 629–653, doi:10.1146/annurev.earth.34.031405.125211.

Höning, D., and Spohn, T., 2016, Continental growth and mantle hydration as intertwined feedback cycles in the thermal evolution of Earth: Physics of the Earth and Planetary Interiors, v. 255, p. 27–49, doi:10.1016/j.pepi.2016.03.010.

Kasting, J.F., and Holm, N.G., 1992, What determines the volume of the oceans? Earth and Planetary Science Letters, v. 109, p. 507–515, doi:10.1016/0012-821X(92)90110-H.

Korenaga, J., 2021, Was there land on the early earth? Life, v. 11, doi:10.3390/life11111142.

Korenaga, J., Planavsky, N.J., and Evans, D.A.D., 2017, Global water cycle and the coevolution of the Earth's interior and surface environment: Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, v. 375, p. 20150393, doi:10.1098/rsta.2015.0393.

Labrosse, S., Hernlund, J.W., and Coltice, N., 2007, A crystallizing dense magma ocean at the base of the Earth's mantle: Nature, v. 450, p. 866–869, doi:10.1038/nature06355.

Li, Y., Sun, T., and Brodholt, J.P., 2020, The Earth's core as a reservoir of water: Nature Geoscience, doi:10.1038/s41561-020-0578-1.

Lourenço, D.L., Rozel, A.B., Gerya, T., and Tackley, P.J., 2018, Efficient cooling of rocky planets by intrusive magmatism: Nature Geoscience, v. 11, p. 322–327, doi:10.1038/s41561-018-0094-8.

Luskin, C., Wilson, A., Gold, D., and Hofmann, A., 2019, The Pongola Supergroup:

Mesoarchaean Deposition Following Kaapvaal Craton Stabilization, *in* p. 225–254, doi:10.1007/978-3-319-78652-0_9.

Marty, B., 2012, The origins and concentrations of water, carbon, nitrogen and noble gases on Earth: Earth and Planetary Science Letters, v. 313–314, p. 56–66, doi:10.1016/j.epsl.2011.10.040.

McLennan, S.M., and Taylor, S.R., 1982, Geochemical Constraints on the Growth of the Continental Crust: The Journal of Geology, v. 90, p. 347–361, doi:10.1086/628690.

Miyazaki, Y., and Korenaga, J., 2022, A wet heterogeneous mantle creates a habitable world in the Hadean: Nature, v. 603, p. 86–90, doi:10.1038/s41586-021-04371-9.

Mojzsis, S.J., Harrison, T.M., and Pidgeon, R.T., 2001, Oxygen-isotope evidence from ancient zircons for liquid water at the Earth's surface 4,300 Myr ago: Nature, v. 409, p. 178–181, doi:10.1038/35051557.

Moore, W.B., 2008, Heat transport in a convecting layer heated from within and below: Journal of Geophysical Research: Solid Earth, v. 113, p. 1–11, doi:10.1029/2006JB004778.

Ohmoto, H., 2020, A seawater-sulfate origin for early Earth's volcanic sulfur: Nature Geoscience, v. 13, p. 576–583, doi:10.1038/s41561-020-0601-6.

Parai, R., and Mukhopadhyay, S., 2018, Xenon isotopic constraints on the history of volatile recycling into the mantle: Nature, v. 560, p. 223–227, doi:10.1038/s41586-018-0388-4.

Pearson, D.G. et al., 2014, Hydrous mantle transition zone indicated by ringwoodite included within diamond: Nature, v. 507, p. 221–224, doi:10.1038/nature13080.

Pope, E.C., Bird, D.K., and Rosing, M.T., 2012, Isotope composition and volume of Earth's early oceans: Proceedings of the National Academy of Sciences of the United States of America, v. 109, p. 4371–4376, doi:10.1073/pnas.1115705109.

Retallack, G.J., and Noffke, N., 2019, Are there ancient soils in the 3.7 Ga Isua Greenstone Belt, Greenland? Palaeogeography, Palaeoclimatology, Palaeoecology, v. 514, p. 18–30, doi:10.1016/j.palaeo.2018.10.005.

Roerdink, D.L., Ronen, Y., Strauss, H., and Mason, P.R.D., 2022, Emergence of felsic crust and subaerial weathering recorded in Palaeoarchaean barite: Nature Geoscience, v. 15, p. 227–232, doi:10.1038/s41561-022-00902-9.

Sandu, C., Lenardic, A., and McGovern, P., 2011, The effects of deep water cycling on planetary thermal evolution: Journal of Geophysical Research: Solid Earth, v. 116, p. 1–16, doi:10.1029/2011JB008405.

Sleep, N.H., Zahnle, K.J., and Lupu, R.E., 2014, Terrestrial aftermath of the Moon-forming impact: Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, v. 372, p. 20130172, doi:10.1098/rsta.2013.0172.

Smithies, R.H., Lu, Y., Kirkland, C.L., Johnson, T.E., Mole, D.R., Champion, D.C., Martin, L., Jeon, H., Wingate, M.T.D., and Johnson, S.P., 2021, Oxygen isotopes trace the origins of Earth’s earliest continental crust: Nature, v. 592, p. 70–75, doi:10.1038/s41586-021-03337-1.

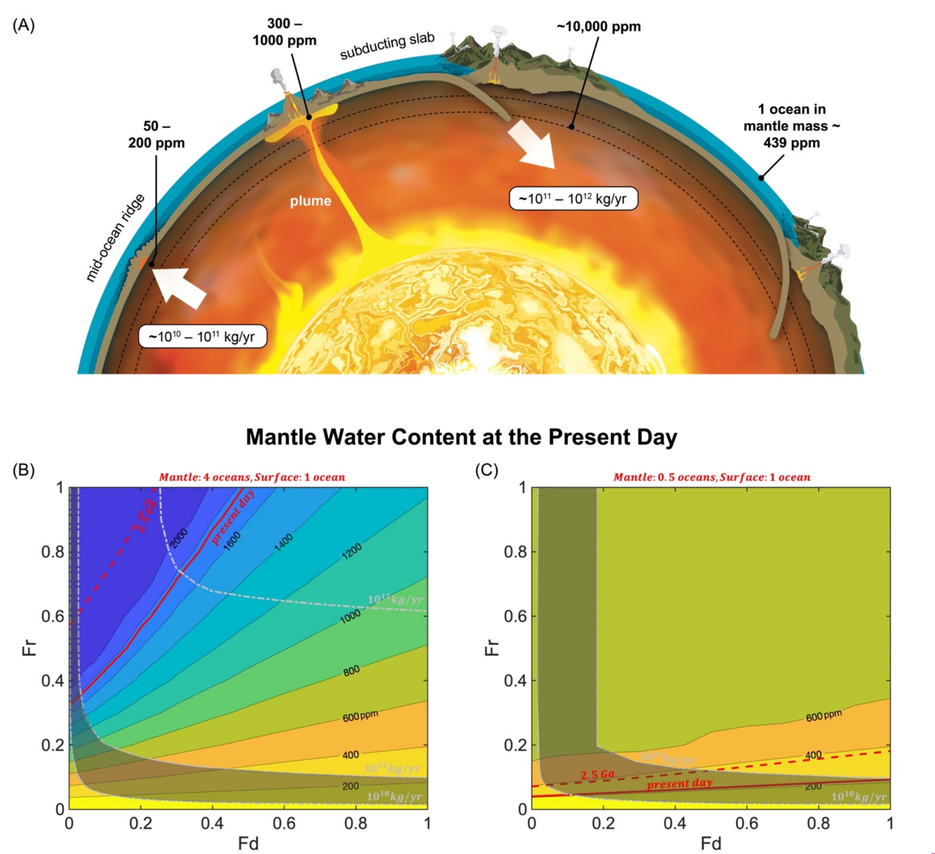
Smyth, J.R., and Jacobsen, S.D., 2013, Nominally Anhydrous Minerals and Earth’s Deep Water Cycle, *in* Earth’s Deep Water Cycle, p. 1–11, doi:10.1029/168GM02.

Stixrude, L., and Lithgow-Bertelloni, C., 2012, Geophysics of Chemical Heterogeneity in the Mantle: Annual Review of Earth and Planetary Sciences, v. 40, p. 569–595, doi:10.1146/annurev.earth.36.031207.124244.

Tikoo, S.M., and Elkins-Tanton, L.T., 2017, The fate of water within Earth and super-Earths and implications for plate tectonics: Philosophical Transactions of the Royal Society A:

Mathematical, Physical and Engineering Sciences, v. 375, p. 20150394, doi:10.1098/rsta.2015.0394.

Windley, B.F., 1977, Timing of continental growth and emergence: Nature, v. 270, p. 426–428, doi:10.1038/270426a0.



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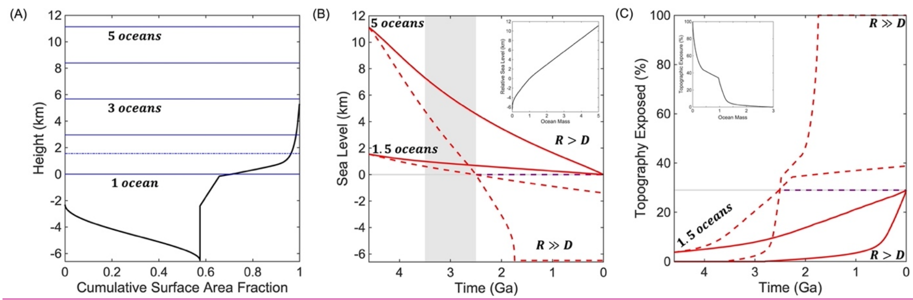
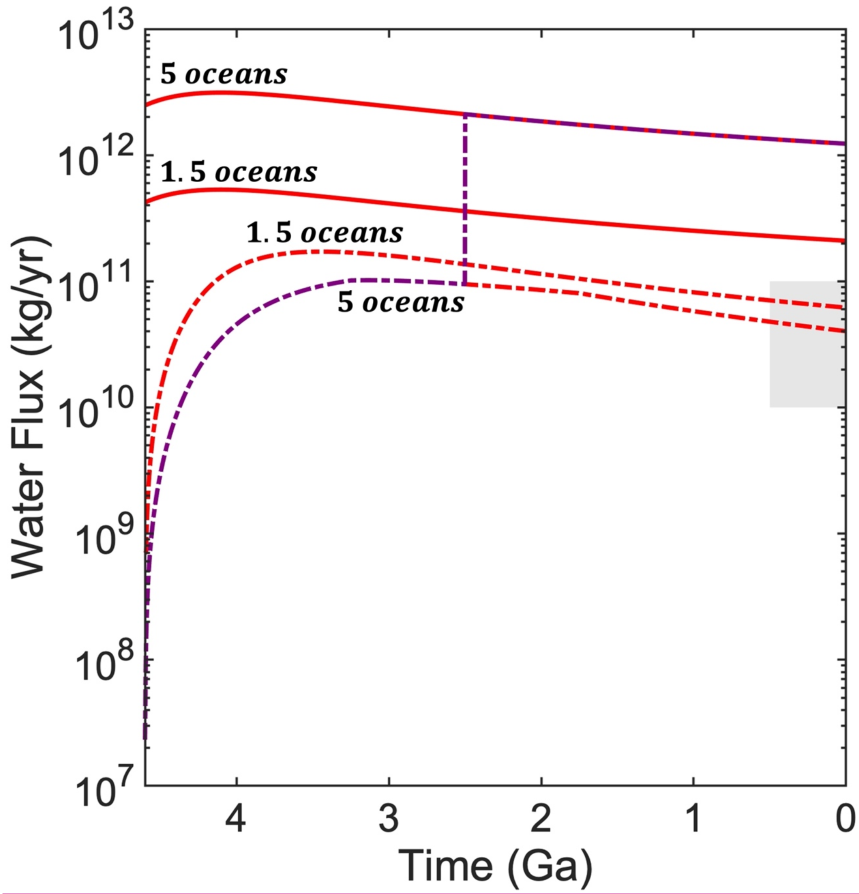


(A)
5 oceans
3 oceans
1 ocean
Height (km)
Cumulative Surface Area Fraction
(B)
5 oceans
1.5 oceans
R > D
R ≫ D
Sea Level (km)
Time (Ga)
Relative Sea Level (km)
Ocean Mass
(C)
R ≫ D
1.5 oceans
R > D
Topography Exposed (%)
Time (Ga)
Topographic Exposure (%)
Ocean Mass



Water Flux (kg/yr)
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
5 oceans
1.5 oceans
1.5 oceans
5 oceans
4
3
2
1
0
Time (Ga)

332

TABLE 1. PARAMETERS FOR THE PARAMETERIZED CONVECTION MODEL RESULTS IN FIGURE 2B

Initial ocean mass	Excess oceans subducted by 0 or 2.5 Ga	F_D	F_R	Surface exposure (%)		
				3.5 Ga	2.5 Ga	Today
5 oceans	0	0.02	0.343	0	0.3	29
5 oceans	2.5	0.01	0.564	0.2	29	100
1.5 oceans	0	0.5	0.066	6	10	29
1.5 oceans	2.5	0.3	0.096	11	29	39

Note: Table shows the surface exposed above sea level after 3.5, 2.5, and 0 Ga for different starting ocean masses. Results are given for cases when the excess oceans (oceans > present-day ocean mass of 1.39 × 10^{21} kg = 1 ocean) are subducted by either 0 or 2.5 Ga. Also given are the corresponding values of regassing (F_R) and degassing (F_D) efficiency.

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