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The Coupled Effects of Mantle Mixing and a Water-Dependent Viscosity on the Surface Ocean

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Abstract

Water content plays a vital role in determining mantle rheology and thus mantle convection and plate tectonics. Most parameterised convection models predict that Earth initially underwent a period of rapid degassing and heating, followed by a slow and sustained period of regassing and cooling. However, these models assume water is instantaneously mixed and homogeneously distributed into the mantle. This is a limitation because the mixing time for water entering and leaving the mantle is a function of the Rayleigh number which varies dramatically with water content, temperature, and through time. Here we present an adapted parametrised model (Crowley et al., 2011) to include the coupled effects of the time scale of mixing with a water-dependent viscosity. We consider two mixing types: first, where the mixing time is constant throughout the model and second, where mixing time varies as a response to an evolving Rayleigh number. We find that, facilitated by the effects of water content in the melt region at mid-ocean ridges, a constant mixing time can induce long periods of degassing. The inclusion of a variable mixing time dependent on the Rayleigh number acts to limit the period of degassing and also results in more water being stored in the mantle and less at the surface than in both the constant and instantaneous mixing cases. Mixing time cannot be more than a few billion years as large mixing times trap water in the mantle, leaving a dry surface. Even small changes in the surface ocean induced by mixing times on the order of 0.1 Gyrs can cause changes in the global-mean sea level on the order of 10's of metres. These changes in sea level could easily uncover topographic highs in the bathymetry, potentially aiding sub-aerial erosion a process thought to be important in early Earth evolution. Even in this relatively simple model, the inclusion of a mixing time between water entering and leaving the mantle creates a more dynamic water cycle.

Keywords: mixing, water-dependent viscosity, sea level, parametrised mantle convection

1. Introduction

1 Viscosity is the determinant physical property
2 in the thermal evolution of the mantle, depend-
3 ent on many parameters including temperature,
4 pressure and grain size but the effect of water
5 is currently undergoing investigation. Labora-
6 tory experiments on olivine have shown that wa-
7 ter content can cause a reduction in viscosity of
8 up to three orders of magnitude (e.g. Mei and
9 Kohlstedt, 2000; Fei et al., 2013) and first prin-
10 ciples simulations on perovskite show almost no
11 effect (Muir and Brodholt, 2018). Understand-
12 ing this relationship between mineral viscosity
13

14 and water content is of particular interest due to
15 the implications for mantle convection and hence
16 planetary evolution. If viscosity can vary several
17 orders of magnitude, the convective vigour could
18 also change by this magnitude with consequences
19 for the style of convection.

20 The effects of a water-dependent viscosity on
21 thermal evolution have been examined previously
22 in parametrised (Crowley et al., 2011; Sandu
23 et al., 2011) and two-dimensional (2D) models
24 (e.g. Nakagawa et al., 2015). Parametrised stud-
25 ies have shown a water-dependent viscosity ini-
26 tially produces a period of heating and a state
27 of net degassing (where degassing at mid-ocean
28 ridges, MORs, exceeds regassing at subduction
29 zones), followed by a long and sustained period
30 of cooling and a state of net regassing (Crow-
31 ley et al., 2011; Sandu et al., 2011). This is due

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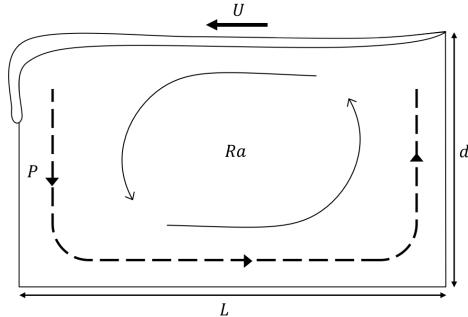


Figure 1: The path, P , from subduction zone to mid-ocean ridge (MOR) represents the path of a subducting package. The time for the package to travel along this path is the mixing time, τ . For constant mixing, τ is constant over the course of the model and the time to get from the subduction zone to the MOR is constant. For variable mixing, τ is proportional to the convective vigour, $Ra^{2/3}$ and hence temperature and water content through viscosity. The travel time between subduction zone and MOR is dependent on the average mantle temperature T and local water content at the ridge X [$\tau_{(Ra)}$], through Ra .

to the rapidly decreasing water content increasing the viscosity, trapping heat and causing the temperature to build up. After some time, the increase in temperature lowers the viscosity and increases Ra such that the mantle starts to convect more efficiently again and the mantle ends up in a period of gradual cooling and regassing. Some models suggest more than one cycle of heating and cooling have occurred over the lifetime of the Earth (Sandu et al., 2011). The initial period of degassing removes almost all of the water from the mantle reservoir resulting in a drier mantle, something that has been suggested to aid the onset of plate tectonics (Korenaga, 2011). A water-dependent viscosity has also been coupled with continent generation showing that increased continental weathering due to the presence of life on Earth favours a wet mantle (Höning et al., 2014; Höning and Spohn, 2016).

One of the biggest assumptions in parametrised models is that mixing of water introduced at subduction zones and extracted at MORs is instantaneous and moreover, water is homogeneously distributed throughout the mantle. This, of course, is a great simplification. It is clear that both water content and mixing time play vital roles in mantle evolution, and the two variables are strongly interdependent. In spite of this, there has been very little work attempting to understand this interdependence or what impact this time delay may have on the evolution of the Earth.

There is a rich literature on dynamical systems with a time-delay, which are found in many fields such as non-linear optics, population dynamics and physiology (May, 1980; Mackey and Glass, 1977; Niculescu et al., 1998). The in-

roduction of a time-delay, such as the mixing time in the mantle, can cause the system to become unstable (Niculescu et al., 1998; Doyne Farmer, 1982). The role of the time-delay has been explored using model equations, such as the Mackley-Glass equation (Mackey and Glass, 1977), in which a progressive increase in the magnitude of the time-delay can cause the system to transition from a simple periodic response to a complex multi-component response and ultimately to chaos (Junges and Gallas, 2012). Such transitions can have a major impact on the final state of the system, and in terms of the mantle, the mixing time has the potential to significantly affect the mantle temperature, rates of mantle convection and sea level. Hence, we impose a mixing time in the water cycle of a thermal evolution model to understand the effects of a heterogeneous mantle water content introduced by subduction.

2. Methods

Consider an Earth-like planet with plate tectonics where a subducted package follows the trajectory shown in Figure 1, travelling a total distance $P = 2d + L$. The time it takes to reach the MOR is the mixing time $\tau = P/U$. τ is also likely to depend on the convective vigour, Ra (where Ra is the ratio of buoyant to dissipative forces). As the velocity $U \propto Ra^{2/3}$ (Turcotte and Oxburgh, 1967), $\tau \propto Ra^{-2/3}$ (Samuel et al., 2011) where mixing time is inversely proportional to convective vigour. This implies that in the past when the mantle was hotter, viscosity was low, Ra was high and the mixing time was short. As it cools, the viscosity increases; Ra decreases and τ becomes longer, assuming plate tectonics has operated since mantle solidification.

2.1. Evolution Model

The evolution is solved by following the procedure outlined by Crowley et al. (2011). The convective vigour is described by the Rayleigh number

$$Ra = \frac{\alpha \rho g T d^3}{\kappa \eta} \quad (1)$$

where α is thermal expansivity, ρ is density, g is gravity, T is average mantle temperature, d is mantle depth, κ is thermal diffusivity and η is viscosity. The conservation of energy

$$\frac{dT}{dt} = \frac{-Q_s + H}{\rho V c_p} \quad (2)$$

and conservation of mass

$$\frac{dX}{dt} = \frac{R - D}{\rho V} \quad (3)$$

115 equations are solved via fourth order Runge-
 116 Kutta (RK4) methods where Q_s is surface heat
 117 flow, H is heating from radiogenic elements, V is
 118 mantle volume, c_p specific heat capacity, average
 119 mantle water content is X , R is regassing and D
 120 is degassing. The conservation of energy depends
 121 on radiogenic heat production, H

$$H = H_{sf} \sum_j \rho C_j H_j \exp\left(\frac{\ln 2 (t_{pd} - t)}{\tau_j}\right) \quad (4)$$

122 H is a sum of the contributions from U^{238} , U^{235} ,
 123 Th and K where C_j is concentration (of the j^{th}
 124 element), H_j is heat production, τ_j is radiogenic
 125 half life and t_{pd} is present day time (Table 1). Eq.
 126 2 also depends on the surface heat flow, Q_s

$$Q_s = 2Sk_c T \left(\frac{U}{\pi L \kappa}\right)^{\frac{1}{2}} \quad (5)$$

127 where U is plate velocity, S is surface area, k_c
 128 is thermal conductivity and L is plate length. Q_s
 129 is a function of U

$$U = \frac{\kappa}{d} \left(\frac{L}{\pi d}\right)^{\frac{1}{3}} Ra^{\frac{2}{3}} \quad (6)$$

130 and is proportional to Ra . Degassing and re-
 131 gassing are also a function of U

$$D = SF_d \frac{z_m}{L} U \rho X \quad (7)$$

$$R = SF_r \frac{d_l}{L} U \rho X_p \quad (8)$$

132 Degassing (Eq. 7) defines the amount of water
 133 removed from the mantle at MORs. It also de-
 134 pends on the melting depth $z_m = z_1 T_p + z_2 X + z_3$,
 135 a parametrised water-dependent melting depth
 136 (Hirschmann et al., 2009; Crowley et al., 2011)
 137 where z_1 , z_2 and z_3 are constants and T_p is po-
 138 tential temperature in degrees celsius (Mckenzie
 139 and Bickle, 1988) which, with water content, var-
 140 ies in time. The mass of melt is given by $z_m U \rho$
 141 and it's water content is defined by the average
 142 mantle water content (when mixing is considered,
 143 this value will differ). Degassing is also depend-
 144 ent on the degassing efficiency, F_d . This constant
 145 defines how much water in the melting region es-
 146 capes to the surface, where 1 = 100% of the water
 147 in the melt region reaches the surface reservoir.

148 Similarly, regassing (Eq. 8) defines the amount
 149 of water subducted into the mantle. It is de-
 150 pendent on the evolving variables of thermal plate
 151 thickness d_l and plate velocity. The thermal
 152 plate thickness is defined by the half space cool-
 153 ing model such that $d_l = 2(\kappa L/U)^{\frac{1}{2}}$. Regassing
 154 efficiency F_r describes the fraction of water that

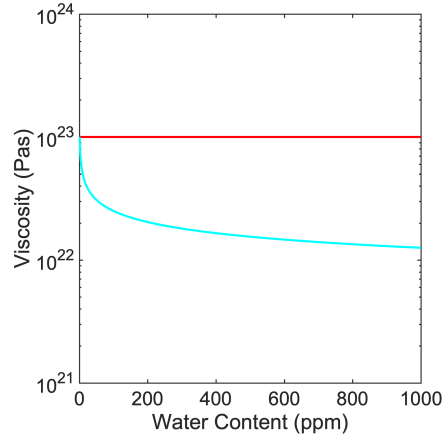


Figure 2: COLOUR Viscosity variation with respect to water content at 2200 K for both viscosity laws used in this model from Eq 9. Both laws are calibrated to give the same viscosity when no water is present (Fei et al., 2013). The water-dependent law, $\eta(T, X)$ varies one order magnitude from up to 1000ppm.

155 makes it past the subduction factory and X_p is an
 156 average plate water concentration. The values of
 157 these constants and others defined here are found
 158 in Table A. 2.

159 2.2. Water-Dependent Viscosity

160 We test two simplified viscosity laws of the form

$$\eta = \eta_0 \left(\frac{X}{X_c}\right)^{-r} \exp\left(\frac{E}{RT}\right) \quad (9)$$

161 η is the viscosity, η_0 is a calibration constant,
 162 E is the activation energy and R is the ideal
 163 gas constant. r is the water content exponent,
 164 controlling whether the law is water-independent
 165 ($\eta(T)$ where $r = 0$) or water-dependent ($\eta(T, X)$
 166 where $r = 0.3$) with an order of magnitude sensi-
 167 tivity to 1000 ppm of water (Fei et al., 2013),
 168 shown in Figure 2. η_0 is chosen such that for an
 169 average mid-mantle temperature of 2200 K and
 170 $\eta(T)$, viscosity is equivalent to a dry mid-mantle
 171 bridgmanite of 10^{23} Pas (Ammann et al., 2010).

172 2.3. Mixing Time

173 The mixing time, τ , is incorporated into the
 174 evolution model in two ways: (1) τ is constant or
 175 (2) τ is variable. Figure 3 illustrates where these
 176 steps occur with respect to solving Eqs. 2 and
 177 3. The incorporation of a mixing time inherently
 178 requires the tracking of two different mantle wa-
 179 ter contents: the whole mantle average X and a
 180 localised water content at the MOR $X[\tau(Ra)]$.
 181 This difference arises as it takes a finite amount
 182 of time for any subducted water to reach a MOR;
 183 this transit time across the conceptual model do-
 184 main (Figure 1) is the mixing time.

185 When mixing is instantaneous i.e. $\tau = 0$,
186 any water subducted into the mantle is homogen-
187 eously mixed into the mantle and can instantly
188 be degassed into the surface ocean. This is rep-
189 resented in Figure 2 by the arrows and lines out-
190 lined in black. Only X and T are used to calcu-
191 late and solve Eqs. 1-9. For a constant mixing
192 time, τ , there is an imposed delay to when wa-
193 ter reaches the ridge, shown by the orange path
194 in Figure 2. This water content is calculated as
195 $X[\tau] = X[t_i - \tau]$. For example, if the mantle
196 starts as dry, melting at the MOR is determined
197 by dry conditions, before any water arrives at the
198 ridge. Now, $X[\tau]$ is used to calculate and solve
199 Eqs. 1-9. Eq. 3 still solves for the average mantle
200 water content, however it is now dependent on
201 the local conditions at the MOR, controlled by
202 $X[\tau]$. The variable mixing time, τ_{Ra} , is calculated
203 as

$$\tau_{Ra} = \tau \left(\frac{Ra[T_i, X_i]}{Ra_{pd}} \right)^{-m} \quad (10)$$

204 where Ra is the Rayleigh number calculated with
205 X_i and T_i , $Ra_{pd} = 10^6$ and $m = 2/3$ is the classical
206 scaling between the plate velocity and Rayleigh
207 number (Eq. 6) for any given τ . τ_{Ra} evolves over
208 the course of the model such that when Ra is high,
209 convection is vigorous and τ_{Ra} is short (and vice
210 versa). $X[\tau_{Ra}] = X[t_i - \tau_{Ra}]$ and Eqs. 1-9
211 are calculated therefore solved with a varying mix-
212 ing time. In order to prevent the appearance of
213 numerical instabilities, the calculation of $X[\tau_{Ra}]$ 239
214 involves iteration outlined in Figure 2. $X[\tau_{Ra}]$ 240
215 is also taken to be the average X found over five 241
216 time steps, centred about τ_{Ra} . 242

217 2.4. Model Set-Up 244

218 Instantaneous mixing cases ($\tau = 0$) are calib- 245
219 rated by tuning the initial ocean mass to give one 246
220 ocean mass (1.39×10^{21} kg) at the present day (4.6 247
221 Gyrs) whilst for constant and variable mixing, 248
222 mantle water content is allowed to evolve freely 249
223 to assess the effects of mixing on the water cycle. 250
224 By tuning H_{sf} , the surface heat flow for all mod- 251
225 els is constrained to be within the range 45 - 46 252
226 TW at the present day (Lay and Buffett, 2008). 253

227 Where the water should reside at the beginning 254
228 of the model is unclear. This model only consid- 255
229 ers convection in a solid mantle and hence assu- 256
230 mptions must be made about what happens to 257
231 water prior to or during the freezing of a magma 258
232 ocean, and also after the Moon-forming impact. 259
233 Water is contributed primarily during planetary 260
234 accretion (Marty et al., 2016), although as the 261
235 planet continues to form, it is unclear where wa- 262
236 ter resides. Impact events can form and degas 263
237 magma oceans and liquid water on the Earth's 264
238 surface during times of giant impacts may be 265

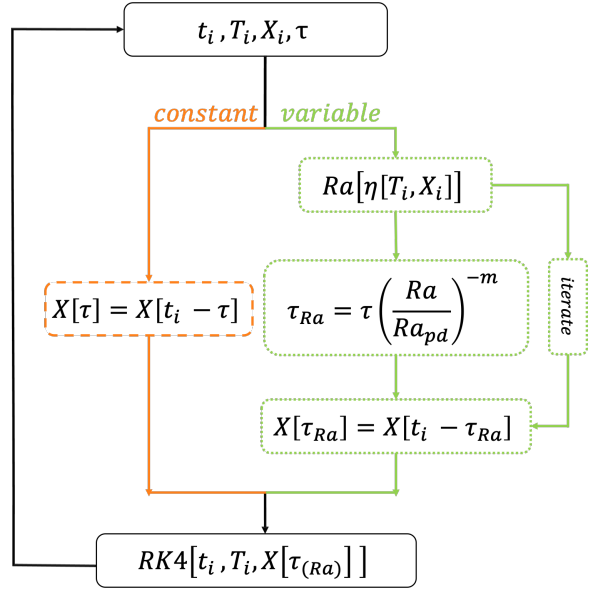


Figure 3: COLOUR Schematic representing the main calculation loop. Solid boxes represent the steps taken in all cases, the orange path with a dashed box represents the additional steps when mixing time is constant and the green path with dotted boxes represents the steps when mixing time is variable. τ is the constant mixing time or the prescribed mixing time that is later scaled by Ra to give τ_{Ra} for variable mixing. Equations 2 and 3 are solved with a fourth order Runge-Kutta solver, RK4 with $X[\tau_{(Ra)}]$ and hence the evolution is dependent on $X[\tau_{(Ra)}]$ i.e. the local water content at the ridge. In contrast, X is the global, average mantle water content, solved for over the course of the model.

likely (Tucker and Mukhopadhyay, 2014). Models of a solidifying magma ocean have shown that the most effective degassing phase of volatiles is during magma ocean solidification (Elkins-Tanton, 2011) but conversely the sinking of hydrous cumulates enriches the upper mantle in water, suggesting that the vast majority of accretionary water can be held in the mantle interior (Tikoo and Elkins-Tanton, 2017). However, these models use mantle water capacity for wadsleyite and ringwoodite at present day mantle temperatures. Water capacity has been shown to decrease with increasing temperatures (Ohtani et al., 2000) and hence today's most hydrous mantle minerals such as wadsleyite and ringwoodite are likely to hold much less than 3000ppm (Ohtani et al., 2000) of water in the past. If the magma ocean is hydrous, as it solidifies the water is expelled to the surface.

Thus far, previous deep water cycle models have also shown that beginning with water in the mantle results in a short period of net degassing (Crowley et al., 2011; Sandu et al., 2011) in which almost all of the water is expelled to the surface. Models with further geochemical, petrological and geological constraints for Earth advocate for a drier mantle in the Hadean in order to take into account the initiation of plate tectonics

	$\eta(T)$	$\eta(T, X)$	Units
$M_s(t_0)$	1.723	1.887	1.39×10^{21} kg
$T(t_0)$		2500	K
H_{sf}	1.706	1.724	-
η_0		7.53×10^{15}	Pas
r	0	0.3	-
R		8.314	$\text{Jmol}^{-1}\text{K}^{-1}$
E		3×10^5	J

Table 1: Starting conditions and viscosity constants for instantaneous mixing cases. For both viscosity laws, the mixing times are tested between 0.002 and 9 Gyrs on the orders of 0.001, 0.01, 0.1 and 1 Gyrs.

(Korenaga, 2011). For these reasons, we assume a dry mantle and a surface reservoir holding approximately two ocean masses of water. Models testing a wet starting condition are discussed in Figures A1 and A2.

We examine a suite of mixing times varying from 0.002 to 9 Gyrs, for constant and variable mixing and each viscosity law (Table 1). The case where the mixing time is 9 Gyrs is equivalent to only regassing operating as no water ever reaches a MOR to be degassed i.e. $X[\tau_{Ra}]$ is always zero. Running models to 9 Gyrs ensures that we capture behaviour of the system until it reaches a steady state.

3. Results

Both the thermal evolution and water cycle can be in two states, depending on whether the input or output of the system is dominant. For thermal evolution, the planet can either be in a state of cooling where $Q_s > H$ or heating where $Q_s < H$. Similarly, the water cycle can be in a state of net regassing where $R > D$ or net degassing where $R < D$. In general, the planet is cooling and regassing as shown previously (Crowley et al., 2011). However, including mixing shows deviation from this trend.

3.1. Water-Independent Viscosity

3.1.1. Instantaneous Mixing

Figure 4 shows selected cases that represent the overall effects of a constant and variable mixing time for 9 Gyrs. The simplest case comprises of $\eta(T)$ with $\tau = 0$, i.e. mixing is instantaneous. The mantle heats then cools to ~ 2000 K (Figure 4a) and increases in water content (Figure 4b) to ~ 425 ppm. As viscosity (Figure 4c) is only dependent on temperature, the increase and decrease in temperature cause a decrease and increase in viscosity, respectively. The melting

depth (Figure 4e) is dependent on both temperature and water content. As a result, during the first 5 Gyrs the change in temperature is more significant than the change in water content and the melting depth decreases with decreasing temperature. After 5 Gyrs, the change in water content is more notable than the change in temperature and melting depth increases with increasing water content. This evolution agrees with previous parametrised studies (e.g. Korenaga, 2011).

3.1.2. Constant Mixing

The addition of a constant mixing time has a pronounced effect in the water cycle, shown in Figure 4 for a sample case of $\tau = 1$ Gyrs. The water cycle has no effect on temperature evolution as $\eta(T)$, hence the differences are best illustrated in Figures 4b, 4d and 4e.

During the first billion years, $X[\tau]$ is zero as no subducted water has reached a MOR (i.e. $t < \tau$). As there is no water feeding the MOR, no water is degassed during this period and the water cycle is in a state of net regassing.

Once $t > \tau$, local water content $X[\tau]$ becomes non-zero as water present in the mantle is sampled by MORs. The increase in local water content and the corresponding increase in melting depth allows degassing to begin. Degassing outpaces regassing and a period of net degassing is induced by ~ 2 Gyrs (Figure 4b). For the remainder of the model, as $X[\tau]$ is lower than X , less water is removed than when mixing is instantaneous. This allows X to increase to above the instantaneous case by 9 Gyrs. Net degassing causes a decrease in average mantle water content, and after 1 Gyrs in $X[\tau]$ as well. Decreasing local water content and melting depth reduces degassing such that net regassing resumes by ~ 3 Gyrs.

3.1.3. Variable Mixing

In general, the introduction of a variable mixing time using ($m = 2/3$) causes various trends of the constant mixing case to resemble those observed for instantaneous mixing. This is the result of the dependency of mixing time on viscosity through Ra . At the beginning of the model, high temperature and low viscosity cause short mixing times, but as the mantle cools and viscosity increases, the mixing time becomes longer (Figure 4f). The period where local water content at the MOR is zero is shorter when the mixing time is variable.

This is illustrated in Figure 4f by the line representing $t = \tau_{Ra}$. The variable mixing case spends less time above the line (where $X[\tau_{Ra}] = 0$) than the constant mixing case. As the mixing time increases, less water reaches MORs and therefore less water can be degassed. This results in the absence of a period of net degassing

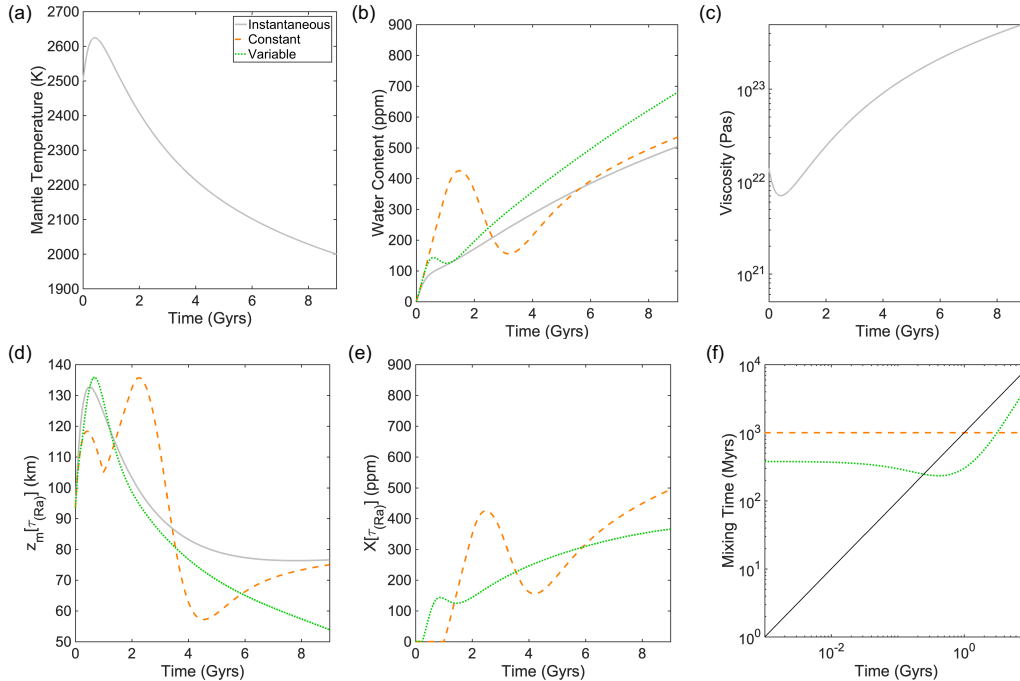


Figure 4: COLOUR Representative cases of a temperature-dependent viscosity law with various mixing implementations, represented by line style. Mixing time $\tau = 1$ Gyrs for both constant mixing and variable mixing (before being scaled by Ra). The panel consist of the resulting (a) mantle temperature T and (b) water content X evolution. The main controls (in no particular) on evolution are (c) viscosity, (d) MOR water content at $t_i - \tau(Ra)$, (e) melting depth and (f) mixing time. Temperature and viscosity evolution are identical for all three mixing cases as rheology is only temperature-dependent. The solid black line in (f) represents the line above which $X[\tau(Ra)] = 0$ and below $X[\tau(Ra)] > 0$ as defined in (d). For constant mixing, the delayed arrival of water at the MOR induces a period of net degassing. When mixing is variable, these effects are damped and net degassing begins earlier and lasts for a shorter amount of time,

360 and more water residing in the mantle for vari- 387
 361 able mixing than instantaneous mixing. 388

362 3.1.4. Influence of Mixing Time Scaling 390

363 The data presented in Figure 4 was calculated 391
 364 using Eq. 10 where $m = 2/3$. To test the effect this 392
 365 scaling has on mantle evolution, we vary m from 0 393
 366 to 1, where $m = 0$ is equivalent to a constant mixing 394
 367 time. The results are shown in Figure 5. As 395
 368 with Figure 4, the temperature (Figure 5a) and 396
 369 viscosity (Figure 5c) are the same for each case. 397
 370 As m is increased, $\tau_{Ra}(t = 0)$ decreases (Figure 398
 371 5f), and for $m = 1$, the unscaled mixing time, τ ,
 372 of 1 Gyrs is reduced by an order of magnitude
 373 to 0.02 Gyrs. This decreases the period where
 374 $X[\tau_{Ra}] = 0$ in which the mantle goes through
 375 fluctuations in water content and an early period
 376 of degassing. This ceases when mixing time
 377 is strongly dependent on Ra ($m \gtrsim 0.8$), where wa-
 378 ter content increases smoothly and no period of
 379 degassing occurs.

380 For cases in which m is small (τ_{Ra} is weakly de- 406
 381 pendent on Ra), the initial period of net regassing 407
 382 is longer, leading to a greater build up of water 408
 383 in the mantle early on: for $m = 0$, X reaches a local 409
 384 maximum of 425 ppm at 1.5 Ga. This excess of 410
 385 water eventually leads to a period of net degass- 411
 386 ing, lasting from 1.5 Ga to 3.2 Ga. For cases with 412

a slightly larger m (mixing time is more sensit-
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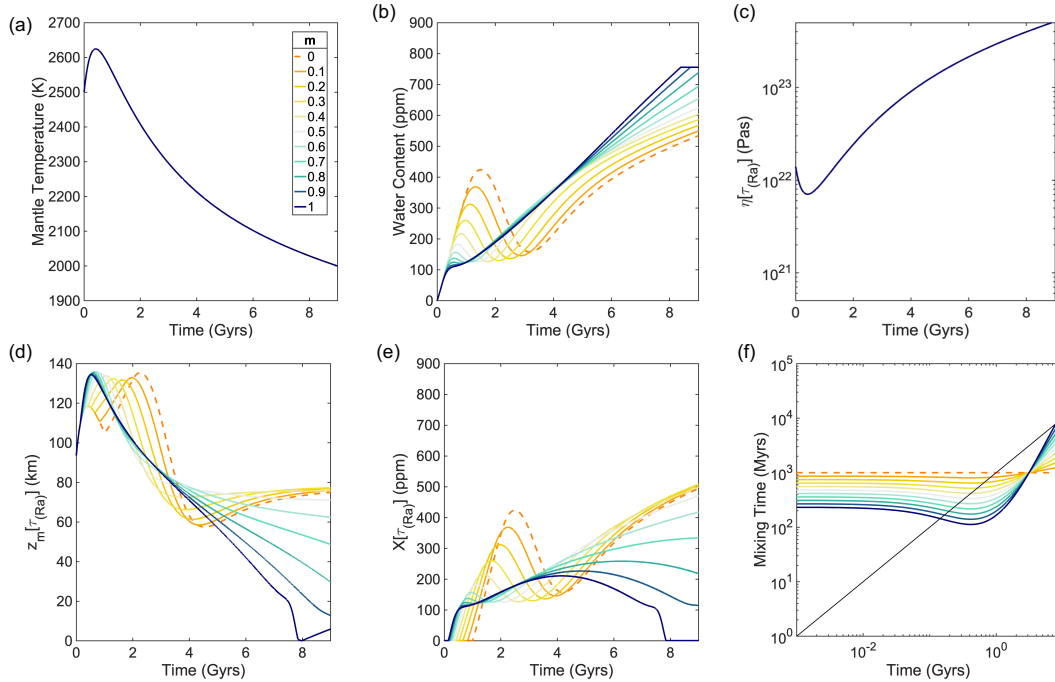


Figure 5: Variation in evolution due to changing m -exponent in the variable mixing time relationship of Eq. 10. (a) average mantle temperature, (b) average mantle water content, (c) average mantle viscosity, (d) melting depth, (e) local water content at MOR and (f) mixing time. $m = 0$ (dashed orange) represents the constant mixing case also presented in Figure 4 and dark blue represents $m = 1$. As the exponent increases, shorter mixing times are achieved at the beginning of the model. This decreases the time the model spends with only regassing operating, eventually removing the period of net degassing and increasing the water content of mantle.

413 The decrease in viscosity allows surface heat flow
 414 to increase until it becomes greater than radiogenic
 415 heating and the mantle cools. The increase
 416 in melting depth and water content during the
 417 period of heating increases degassing. However,
 418 regassing remains dominant and the water cycle
 419 is in a state of net regassing for the entire model.

420 3.2.2. Constant Mixing

421 Implementation of a constant mixing time has a
 422 similar effect as when $\eta(T)$. Some of the extreme
 423 variations in the mixing depth and other prop-
 424 erties that were seen in the water-independent case
 425 have been damped; for constant mixing, the peak
 426 water content in the early Earth ($t < 4$ Ga) is 443
 427 ppm. The oscillations in water content are associ-
 428 ated with changes in the viscosity (Figure 6c) and
 429 therefore also affect mantle temperature (Figure
 430 6a), which both exhibit fluctuations for $t < 4$ Ga.

431 During the first billion years when $X[\tau] = 0$,
 432 heating is more pronounced than in the instant-
 433 aneous mixing case. The water subducted during
 434 this time has not reached a MOR and therefore,
 435 surface heat flow is only dependent on temperat-
 436 ure as before. The mantle feeding MORs is dry,
 437 local viscosity is relatively high and surface heat
 438 flow is lower than radiogenic heating. The mantle
 439 heats faster than the instantaneous case causing
 440 viscosity to decrease. This allows surface heat

441 flow to increase until it becomes greater than ra-
 442 diogenic heating and the mantle begins to cool.

443 After 1 Gyrs, $X[\tau] > 0$ and water subducted
 444 previously reaches the MOR. The increase in $X[\tau]$
 445 decreases local viscosity at the MOR, increasing
 446 surface heat flow and causing a period of rapid
 447 cooling. As temperature rapidly decreases and
 448 local MOR water content increases (Figure 6e), a
 449 local maximum in the melting depth forms (Fig-
 450 ure 6d), and degassing increases.

451 Around 2.5 Gyrs, $X[\tau]$ decreases with decreas-
 452 ing temperature, rapidly decreasing the melting
 453 depth. This reduces degassing and regassing dom-
 454 inates for the remainder of the model.

455 3.2.3. Variable Mixing

456 The final layer of complexity comes with in-
 457 cluding a variable mixing time. As with $\eta(T)$,
 458 variable mixing closely resembles instantaneous
 459 mixing where a shorter mixing time at the be-
 460 ginning of the model causes a shorter period in
 461 which $X[\tau_{Ra}] = 0$ (Figure 6e and 6f). Less wa-
 462 ter is subducted and net degassing is no longer
 463 induced. However, unlike the water-independent
 464 case, mantle water content (Figure 6b) exhibits
 465 stability for 0.2 Gyrs, which suggests that varying
 466 τ before it is scaled by Ra may cause net degas-
 467 sing to reappear for $\tau \neq 1$ Gyr (Eq. 10). Differ-
 468 ences in local viscosity and temperature evolution are also

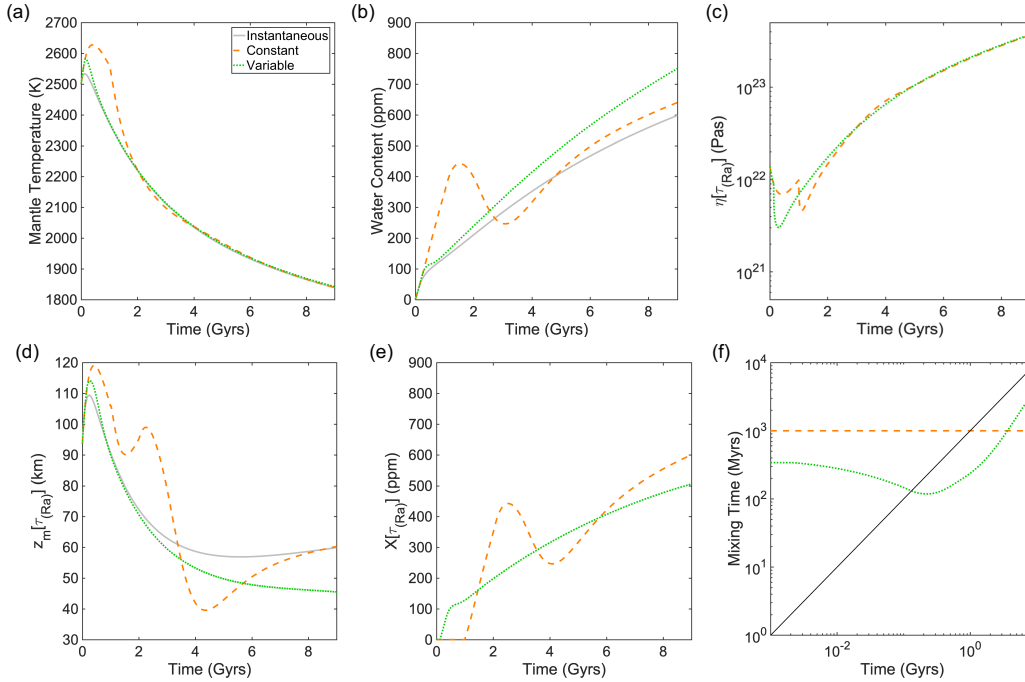


Figure 6: COLOUR Representative cases of a water-dependent viscosity with various mixing implementations where $\tau = 1$ Gyrs for both constant mixing and variable mixing (before being scaled by Ra). (a) is average mantle temperature and (b) is average mantle water content. When mixing is instantaneous, (c) represents the average mantle viscosity and when mixing is included (constant or variable), (c) represents the local viscosity at the MOR. (d) is the melting depth, (e) is local water content at the MOR and (f) is the mixing time. Overall, the results are similar to those of the water-independent viscosity shown in Figure 4, but periods of degassing are damped. Due to the (e) water-dependent viscosity, there is also feedback to the temperature evolution through the surface heat flow.

469 more comparable to those when mixing is instant- 497
 470 aneous as the effects of degassing are dampened 498
 471 by variable mixing. 499

472 3.2.4. Influence of Mixing Time Scaling 501

473 Varying m when $\eta(T, X)$ has similar effects as 502
 474 when examining the differences seen in Figures 503
 475 4 and 6; the initial scaled mixing time (Figure 504
 476 7f) has a range of one order of magnitude with 505
 477 $m = 1$ resulting in 0.1 Gyrs. This dampening 506
 478 effect of $\eta(T, X)$ results in less extreme behaviour. 507
 479 As with Figure 6, there is also a feedback to the 508
 480 temperature (Figure 7a) and viscosity (Figure 7c) 509
 481 evolution. As with the water-independent case 510
 482 (Figure 5), a period of net degassing is induced 511
 483 for $m \leq 0.5$, showing that if the mixing time does 512
 484 not vary by orders of magnitude, net degassing is 513
 485 expected. 514

486 In summary, for a mixing time of 1 Gyrs, constant 515
 487 mixing ($m = 0$) induces a period of net 516
 488 degassing whilst variable mixing dampens that 517
 489 effect and resembles the instantaneous case (for 518
 490 $m > 0.8$). A constant mixing time assumes sub- 519
 491 ducted water takes 1 Gyrs to reach a MOR. This 520
 492 leads to an early build up of water in the mantle 521
 493 and a period of degassing as the mantle readjusts. 522
 494 In contrast, for cases where the mixing time is 523
 495 strongly dependent on Ra (i.e. for $m \gtrsim 0.8$), the 524
 496 greater mantle temperatures in the early Earth 525

ensure τ_{Ra} is very small for much of Earth's history and as a result the mantle evolution closely resembles that seen for the instantaneous mixing case.

As the model progresses ($t \gtrsim 4$ Ga), the trends in temperature (Figure 7a) converge whilst trends in water content deviate. This is due to the deviations in $X[\tau_{Ra}]$, as result of the variable mixing time (Figure 7f). This indicates that even a weak dependence of mixing time on mantle conditions (i.e. Ra) is sufficient to cause the mantle temperature evolution in the present day to resemble the idealised case of instantaneous mixing.

The mantle evolution is most sensitive to the mixing time in the early Earth; this is unsurprising, given this is the period in which changes in Ra are most rapid. The mantle evolution appears to be very sensitive to the mixing time at $t = 0$, as this can lead to a build up of large quantities of water in the mantle followed by a period of degassing, highlighting the importance of initial conditions in the mantle for the evolution of the planet.

4. Discussion

4.1. Periods of Net Degassing

In Figures 4 - 7, we present only the cases of mixing where $\tau = 1$ Gyrs. However, estimates

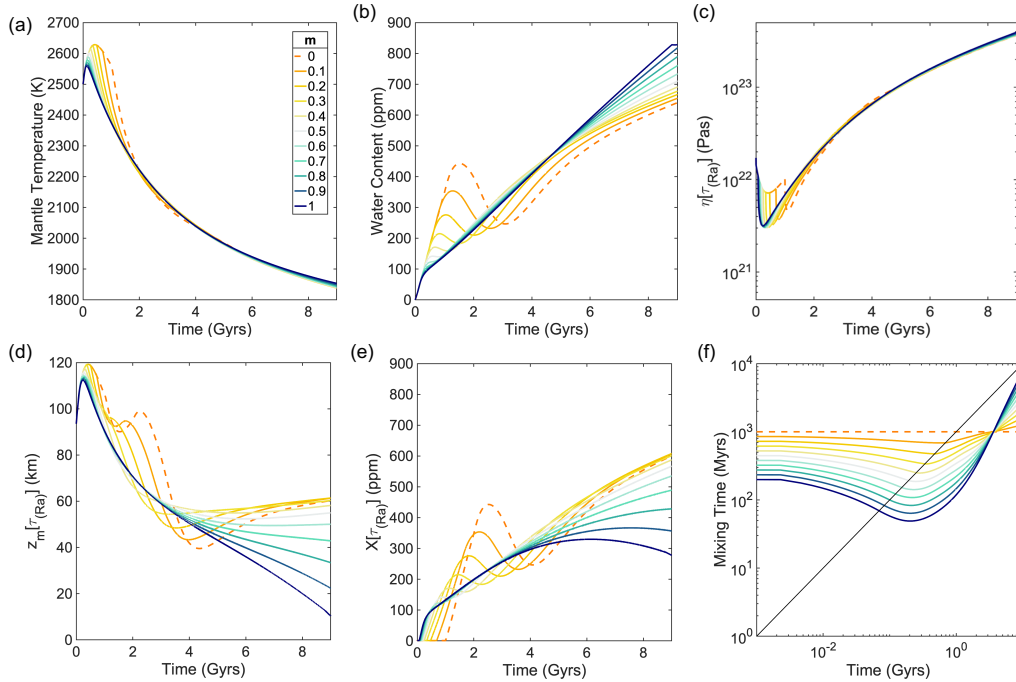


Figure 7: COLOUR Variation in evolution due to changing m -exponent in the variable mixing time relationship for a water-dependent viscosity. $m = 0$ represents the constant mixing case. The results are similar to those of the water-independent viscosity shown in Figure 5, although the water-dependent viscosity tends to damp regassing and degassing near the start of the model. Deviation in (e) local water content is a result of increasing (f) mixing time, effectively trapping water in the mantle.

524 for the present day mixing time for Earth vary 554
 525 from a few hundred million years to a few billion 555
 526 years (Kellogg and Stewart, 1991; Samuel et al., 556
 527 2011). This will inevitably have an impact on the 557
 528 transitions between regassing and degassing in the 558
 529 water cycle presented in the previous section. 559

530 When a mixing time is present, the water cycle 560
 531 can go through three phases: (1) initial net regass- 561
 532 ing when $X[\tau_{(Ra)}] = 0$, (2) net degassing when 562
 533 $X[\tau_{(Ra)}]$ initially becomes non-zero and (3) net 563
 534 regassing for the remainder of the model. These 564
 535 timings can be examined by extracting the turning 565
 536 points in X . These points represent where 566
 537 $\frac{dX}{dt} \sim 0$, i.e. when net degassing begins or ends. 567
 538 Figure 8 presents data from the four different 568
 539 suites of models (constant and variable mixing 569
 540 for both water-independent and water-dependent 570
 541 viscosity laws) considered in the previous section, 571
 542 but here τ varies between 0.002 and 9 Gyrs. 572
 543 Cases with variable mixing times were performed using 573
 544 $m = 2/3$. Figure 8a shows the constant mixing 574
 545 time case for a water-independent viscosity where 575
 546 there are two turning points; the first indicates 576
 547 the start of net degassing and the second indic- 577
 548 ates the end of net degassing. For $\tau < 0.2$ Gyrs, 578
 549 there are no turning points and the water cycle 579
 550 is always in a state of net regassing, behaving al- 580
 551 most identically to the instantaneous mixing case. 581
 552 For $\tau > 0.2$ Gyrs we see the beginning and end 582
 553 of a net degassing period. In general, as the mix- 583

ing time increases, both the start and end of net 584
 degassing are delayed and the duration of net de- 585
 gassing increases. The first turning points follow 586
 a linear trend as the onset of water's influence on 587
 degassing is controlled by the end of the period 588
 where $X[\tau]$ is zero. The end points follow a linear 589
 trend until after $\tau = 2.5$ Gyrs where end times 590
 begin to deviate. 591

Figure 8b shows two suites of data for constant 592
 mixing and a water-dependent viscosity. The 593
 net degassing region looks similar to the water- 594
 independent viscosity case (Figure 8a) with the 595
 period starting later and ending earlier. Unlike 596
 $\eta(T)$, the surface heat flow has to be scaled in 597
 order for the 46 TW condition to be met (Table A3) 598
 further shortening the duration of net degassing. 599

The addition of a variable mixing time has a 600
 drastic impact on net degassing. For a water- 601
 independent viscosity shown in Figure 8c, a 602
 period of net degassing only occurs for $\tau = 0.8$ 603
 - 2 Gyrs lasting ~ 0.3 - 1.4 Gyrs, respectively. 604
 In contrast, for the same period in constant mixing, 605
 net degassing lasts ~ 1.4 - 3.5 Gyrs, respectively. 606
 The period also occurs much earlier for variable 607
 mixing starting ~ 0.6 - 1 Gyrs when $\tau = 0.8$ - 608
 2 Gyrs compared with ~ 1.2 - 3 Gyrs for constant 609
 mixing, respectively. Hence, a variable mixing 610
 time causes net degassing to occur earlier and 611
 for a much shorter period, i.e. the start occurs 612
 later and the end occurs earlier, and only for a 613

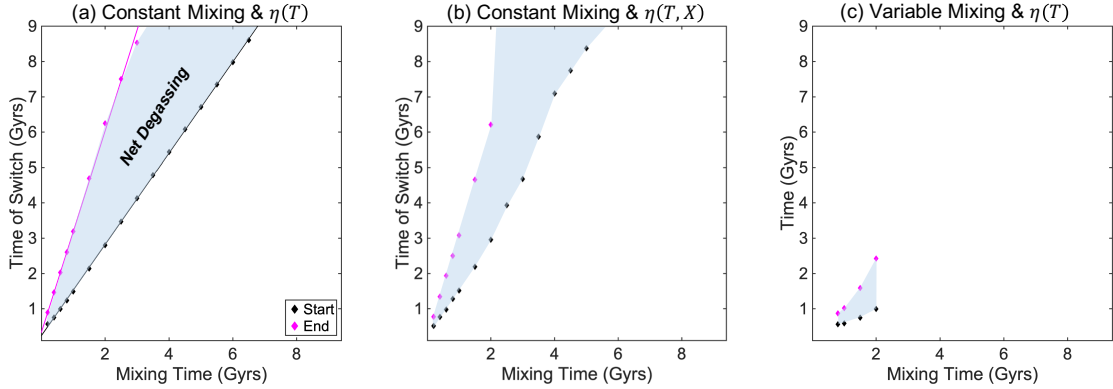


Figure 8: COLOUR The start (black diamonds) and end (magenta diamonds) of periods of net degassing for constant mixing, variable mixing, and both viscosity laws, for τ varying between 0.002 and 9 Gyrs. The y-axis corresponds to the x-axis in Figures 4 to 7. Where there are no points, no net degassing period occurs. A linear trend is fitted to $\tau_{(Ra)} < 2$ Gyrs. Shaded regions corresponds to net degassing. The water-dependent viscosity shortens the period of degassing whilst variable mixing severely restricts the occurrence of degassing. No net degassing period occurs for variable mixing and water-dependent viscosity.

584 limited range of τ .

585 When viscosity is dependent on water and the 624
 586 mixing time is variable, no net degassing occurs. 625
 587 This is due to the relatively short τ_{Ra} , calculated 626
 588 (Eq. 10) as a result of increasing mantle temper- 627
 589 ature and increasing mantle water content, both 628
 590 decreasing Ra . The effect of water content on vis- 629
 591 cosity (Eq. 9) and hence Ra reduces τ_{Ra} pushing 630
 592 evolution to behave more like the instantaneous 631
 593 mixing case where $\tau = 0$. It is more likely to ob- 632
 594 serve short periods of stability or slower changes 633
 595 in water content. For example, cases where $\tau =$ 634
 596 1 - 2 Gyrs, the water content evolution behaves 635
 597 as in Figure 6b where mixing is variable. These 636
 598 results demonstrate how the existence and dura- 637
 599 tion of a period of degassing is very sensitive to 638
 600 both the mantle viscosity and the estimates of the 639
 601 mantle mixing time.

602 When exploring the influence of mixing time, 640
 603 the inverse relationship is seen. For example, Fig- 641
 604 ure 9a shows periods of net degassing as a function 642
 605 of m in Eq. 10 for $\eta(T, X)$ (Figure 7). Increasing 643
 606 m decreases the time period when $t < \tau_{Ra}$, there- 644
 607 fore less water is solely regassed and the later in- 645
 608 fluence on melting depth is not as evident. Mixing 646
 609 becomes more dependent on mantle conditions as 647
 610 m increases and as result, net degassing occurs 648
 611 earlier and lasts for a shorter period of time. 649

612 By varying both τ and m , behaviour in the first 650
 613 ~ 4 Gyrs is dominated by evolution in the first few 651
 614 hundred million years. This implies that the history 652
 615 of the the mantle water content and surface 653
 616 ocean is very sensitive to the initial mixing condi- 654
 617 tions. As such, we also test cases where the start- 655
 618 ing condition has a wet mantle and a dry surface 656
 619 (Figure A1 and A2). The evolution is character- 657
 620 ised by a rapid period of net degassing followed 658
 621 by the same behaviour as described above. This 659
 622 suggests that regardless of the starting conditions, 660

net degassing may occur.

623 The net degassing period will also depend on 624
 625 the efficiency of the degassing process. $F_d = 1$ 626
 627 in all of these models, assuming the most efficient 628
 629 transport to the surface. Whilst lower values are 630
 631 unexpected (Rüpke et al., 2013), values of F_d rang- 632
 633 ing from 0 to 1 are tested (Figure A3) show that 634
 635 the amplitude of net degassing is most affected. 636
 637 $F_d < 1$ decreases how much water is degassed, 638
 639 though there is little change in the start and end 640
 641 times of the net degassing period. Further de- 642
 643 creasing $F_d < 0.4$ stops net degassing from occur- 644
 645 ring where $F_d = 0$ results in an evolution where 646
 647 only regassing operates.

4.2. Surface Ocean Volume

648 Figure 9b shows the surface ocean volume at 4.6 649
 650 Gyrs of each case examined in Figure 8. When the 651
 652 surface ocean is zero, all the water has been sub- 653
 654 ducted into the mantle (Table 1). The majority of 655
 656 cases show less water at the surface at 4.6 Gyrs 657
 658 than for the instantaneous mixing case, i.e. where 659
 660 $\tau = 0$; as the mixing time increases, the surface 661
 662 ocean volume decreases. Deviations from these 663
 664 features are between 0.5 and 4 Gyrs. These cases 665
 666 finish during or soon after the end of a period of 667
 668 net degassing. As net degassing lowers average 669
 670 mantle water content X , more water is found in 671
 672 the surface reservoir. These cases can end with a 673
 674 larger surface ocean than the instantaneous case. 675
 676 Even if these cases have gone through the end of 677
 678 net regassing, it still takes time for water con- 679
 680 tent to recover and to be returned to the mantle. 681
 682 Therefore, cases that do not finish in a state of net 683
 684 degassing can still feel the effects of this period. 685

686 Constant mixing cases (orange in Figure 9b) 687
 688 can show high surface ocean volumes in compar- 689
 690 ison to the instantaneous case. Periods of net 691
 692 degassing are longer allowing more water to be 693

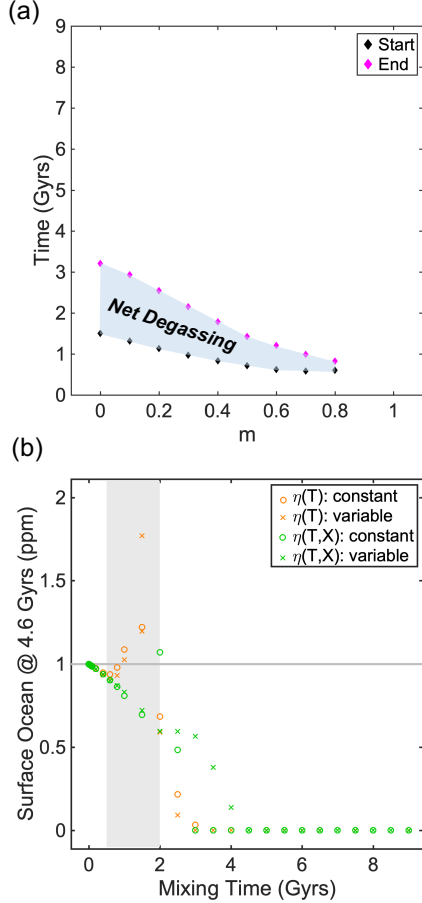


Figure 9: COLOUR (a) Net degassing region for variations in m , akin to those in Figure 8. As m increases, net degassing starts earlier and lasts for shorter periods. (b) number of surface oceans at 4.6 Gyrs in each of the models in Figure 8, normalised by Earth’s present day ocean volume (1.39×10^{21} kg). Mixing cannot be more than a few billion years as otherwise, this would leave a dry surface. The light grey shaded region corresponds to 0.5 - 2 Gyrs mixing time estimates from geochemistry and the dark grey line is equivalent to one ocean mass (~ 439 ppm). The cases that best match both mixing and surface ocean constraints show constant mixing with $\eta(T)$ or $\eta(T, X)$ and variable mixing with $\eta(T)$ are equally likely.

661 released to the surface reservoir, resulting in less
 662 water in the mantle. When mixing is variable and
 663 the viscosity law is also water-dependent the sur-
 664 face ocean volume decreases and the effect of net
 665 degassing in the few cases where it does occur, is
 666 negligible. It is clear from Figure 9b, that when
 667 mixing is included, variations in the surface ocean
 668 mass and hence the average mantle, can be up to
 669 an ocean. In general, as the mixing time is in-
 670 creased, the size of the surface ocean diminishes,
 671 unless the model is in a state of net degassing or
 672 is still recovering from one.

673 4.3. Implications for Earth

674 Thus far, this study has shown that Earth may
 675 go through more than one transition in the water

676 cycle. It is clear that the incorporation of mix-
 677 ing time into the parametrised model has a large
 678 effect on the water content and can lead to exten-
 679 ded periods of net degassing. Constant mixing
 680 ‘locks’ water in the mantle for a finite period of
 681 time. However, for variable mixing, cooling acts
 682 to progressively increase the mixing time, effect-
 683 ively trapping water in the mantle. As the mixing
 684 time increases, mixing becomes more inefficient
 685 and it takes longer for water to reach a MOR.
 686 Less water is available to be degassed, trapping
 687 water at depth and keeping the mantle in a state
 688 of net regassing.

689 The cases presented are in agreement with oth-
 690 ers (e.g. Korenaga et al., 2017; Nakagawa and
 691 Spiegelman, 2017) where net regassing dominates.
 692 However, unlike previous parametrised models,
 693 we start with a large surface ocean rather than
 694 a hydrous mantle (Crowley et al., 2011; Sandu
 695 et al., 2011). This results in the loss of an ini-
 696 tial degassing phase that stiffens the mantle and
 697 induces heating (also present when models start
 698 with wet mantle), although heating is still induced
 699 by the lack of water in the mantle at the begin-
 700 ning of the model. Cases with variable mixing
 701 are also in agreement with previous models where
 702 the mantle is not only hotter, but drier in the
 703 past, particularly during 0.5 and 2 Gyrs, corre-
 704 sponding to the Archean for Earth. As the planet
 705 has cooled, mixing time increases with decreas-
 706 ing Ra and the propensity to degas the mantle
 707 reservoir diminishes. When comparing Figure 9b
 708 with current estimates for mixing times, 0.5 – 2
 709 Gyrs (Gonnermann and Mukhopadhyay, 2009),
 710 and the present day ocean, only a few cases lie
 711 close to this range. Of these cases, none have
 712 a water-dependent viscosity and variable mixing
 713 time. The three closest points to one ocean mass
 714 and within $\tau = 0.5 - 2$ Gyrs are $\tau = 0.8$ Gyrs
 715 where mixing is constant and $\eta(T)$, $\tau = 1$ Gyrs
 716 where mixing is variable and $\eta(T)$ and $\tau = 2$ Gyrs
 717 where mixing is constant and $\eta(T, X)$. However
 718 of these combinations, it is unclear which is most
 719 representative of Earth. It is clear that the mix-
 720 ing time cannot be more than a few billion years
 721 as otherwise water would be perpetually trapped
 722 in the mantle, never released to the surface.

723 Mixing has the greatest effect on temperature
 724 and water evolution when viscosity is independent
 725 of water content. Even if viscosity is not depend-
 726 ent on water (Muir and Brodholt, 2018), the wa-
 727 ter content in the melting region has the largest
 728 effect as D is directly affected by X , pushing the
 729 system into a state of net degassing. Present day
 730 mixing times from geochemistry vary from ~ 0.5
 731 - 2 Gyrs and up to ~ 1 Gyrs from geodynamic
 732 models (Tackley, 2015). But how this mixing time
 733 might have changed over the course of Earth evol-

734 tion is unclear. For early Earth, Hadean mixing 792
735 times on the scale of 0.1 Gyrs are predicted from 793
736 geodynamic models with a mobile lid i.e. plate 794
737 tectonics (e.g. Samuel et al., 2011; Kellogg and 795
738 Stewart, 1991) whereas mixing in a stagnant lid 796
739 model by O’Neill et al. (2013) suggests timescales 797
740 more comparable to those presented by geochem- 798
741 istry, approximately 1 Gyrs, when tectonic regime 799
742 is take into account. Constant mixing (Figure 9b) 800
743 shows two cases that potentially match one sur- 801
744 face ocean at 4.6 Gyrs. Whilst there is uncer- 802
745 tainty in mixing style (constant or variable) and 803
746 the sensitivity of the mantle viscosity to water 804
747 content (negligible or up to three orders of mag- 805
748 nitude), it is clear that changes in the amount of 806
749 water in the melt region at MORs can cause sig- 807
750 nificant changes in the water cycle. This suggests 808
751 that this effect of water content in the MOR re- 809
752 gion coupled with mixing may be more important 810
753 than its relationship with viscosity when consid- 811
754 ering whole mantle evolution. 812

755 It is also interesting to consider the effect of 813
756 a constant or variable mixing time on the over- 814
757 all behaviour of Earth as a dynamic system. For 815
758 the case of instantaneous mixing (Figure 6a), the 816
759 Earth appears to behave similar to a simple first 817
760 order system, where the mantle temperature de- 818
761 clines continuously, with the rate of decay de- 819
762 creasing with time. The introduction of a con- 820
763 stant mixing time leads to fluctuations in the tem- 821
764 perature signal (Figure 6a), similar to those seen 822
765 in the early experimental study of time-delay sys- 823
766 tems by Callender et al. (1936). These fluctu- 824
767 ations are less apparent when the mixing time is 825
768 allowed to vary with time (Figure 7a), especially 826
769 for $m \gtrsim 0.2$; the apparent stabilisation of the sys- 827
770 tem (and the resulting suppression of the period 828
771 of net degassing) arises due to the reduction in the 829
772 magnitude of the mixing time for large m (Figure 830
773 7f). This observation is consistent with previous 831
774 studies of time-delay systems, for which complex 832
775 dynamics and chaos occur when the time-delay 833
776 is of a similar order to the characteristic response 834
777 time of the system (Junges and Gallas, 2012). For 835
778 much of the Earth’s history, radiogenic heating 836
779 has been responsible for the majority of heat flow 837
780 through the mantle, and thus the time-scale of 838
781 long term thermal evolution of the mantle is given 839
782 by the relevant half lives, i.e. 1-10 Gyrs (Table 840
783 A1). By the time the mantle has cooled suffi- 841
784 ciently for mixing time to reach values comparable 842
785 to the radiogenic time-scales (i.e. $\tau_{Ra} = 1$ Gyrs, 843
786 when chaotic behaviour may be expected), fluctu- 844
787 ations in the temperature and water content are 845
788 likely to have died out and the mantle is charac- 846
789 terised by gradually decreasing temperature and 847
790 increasing water content. In such a quasi-steady 848
791 state, the mixing time will have a negligible effect 849

in the long term. However, this may not be the case in the first few billion years, where the time-scales of mixing will be more comparable to the time-scales on thermal evolution.

These changes induced by the lag between regassing during subduction and degassing at MORs also has an effect on the surface reservoir (Figure 9b). On Earth, as little as ± 1 ppm can cause a change in today’s global-mean sea level of ± 10 m, indicating a significant contribution of mantle water to changes in sea level even if changes in the surface reservoir are on the order of a few ppm. Figure 9b shows that these changes occur over hundreds of millions or billions of years. Today, global-mean sea level is rising at a rate of ~ 3 mm/yr (Watson et al., 2015) whereas changes in the constant mixing case (Figure 4) are of the order 10^{-3} mm/yr. On short time-scales, the mantle water contribution may not have much of an impact compared to ice sheet formation and other factors but over the evolution of the Earth would causes significant changes in the surface ocean volume and water content of the mantle. Even with lower estimates of mixing time (< 1 Gyrs), changes in surface ocean mass can be of up to 0.1 ocean masses, which would change sea level by ~ 400 m. During the initial phase of net regassing, the surface ocean diminishes and loses ~ 1 ocean to the mantle leaving less than an ocean at the surface, which could easily uncover highs in the sea floor. For the Earth, we can consider the onset of plate tectonics ~ 2.5 Ga or earlier. If we assume that this is also the beginning of the relatively efficient transport of water into the deep mantle, topography could easily become uncovered and enhance subaerial weathering, an important process aiding the formation of continental crust (Höning et al., 2014). Sea level is the ideal observable to consider with further constraints on the surface ocean from geological data (e.g. Korenaga et al., 2017). Tracking the sea level on the time scale since the break up of Pangea has shown a decrease in ocean mass (Karlsen et al., 2019). Further models in times of sustained super continents with plate reconstructions could show delays between period of rapid subduction and supercontinent break-up in response to melting of relatively hydrated material. Understanding transitions on the billion year time scale requires a different set of tools. Recent work on atmospheric xenon isotopes has shown that there has been at least one transition from net degassing to regassing (Parai and Mukhopadhyay, 2018) on the billion year timescale and further work with this outlook could illuminate more times in Earth’s history when similar transitions may occur. This would also require understanding how water is transported in different tectonic

regimes (e.g. Sleep et al., 2014) such as heat pipe (Moore and Webb, 2013), ‘squishy lid’ tectonics (Lourenço et al., 2018) and incorporation into complex, 2D and 3D models. Hints of net degassing have been seen in 2D (Nakagawa and Nakakuki, 2019) and 3D (Price et al., 2019) models, but not yet discussed. Nakagawa and Nakakuki (2019) show transitions on 0.1 Gyrs scale whereas Price et al. (2019) show cases where net degassing occurs for 0.5 Gyrs. Variations are on the scale of 130ppm which would correspond to changes in over 1km of sea level. Further dimensional models investigating these changes are required to aid the understanding of mixing and it’s impact on the surface ocean.

5. Conclusions

We present a parametrised model (Crowley et al., 2011) adapted to include the coupled effects of mixing and a water-dependent viscosity to explore the effects of mixing on mantle water content and surface ocean volume. The introduction of a second water content $X [\tau_{(Ra)}]$ results in degassing controlled by a local water content, different from the average mantle water content. This results in a period of net degassing where mantle water content decreases and the surface ocean volume increases. The impact of changing water content in the melt region facilitates the appearance of a net degassing period, having a larger effect on the overall water cycle evolution than a water-dependent viscosity. The mixing time itself cannot be more than a few billion years as values greater than this would result in a dry surface. Lastly, even small variations in ocean mass can cause large variations in sea level and once subduction became a viable water transport mechanism, it may have aided sub-aerial weathering in the Early Earth.

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Parameters	Symbol	Value				Units
present day time	t_{pd}	4.6				Gyrs
thermal expansion	α	2.5×10^{-5}				K^{-1}
density	ρ	3500				kgm^{-3}
gravity	g	10				ms^{-2}
mantle depth	d	2.88×10^6				m
mantle volume	V	9.05×10^{20}				m^3
surface area*	S	71%				-
average plate length	L	$2d$				m
thermal diffusivity	κ	8.57×10^{-7}				m^2
specific heat capacity	c_p	1000				$\text{Jkg}^{-1}\text{K}^{-1}$
thermal conductivity	k_c	3				$\text{Wm}^{-1}\text{K}^{-1}$
degassing efficiency	F_d	1				-
regassing efficiency	F_r	0.15				-
plate water content	X_p	2056				ppm
melting depth constants**	z_1	286				mK^{-1}
	z_2	164				mppm^{-1}
	z_3	-3.266×10^5				m
elements	j	U ²³⁸	U ²³⁵	Th	K	-
concentration	C_j	30.8	0.22	124	36.9	$10^{-9} \text{ kgkg}^{-1}$
heat production	H_j	9.46	56.9	2.64	2.92	10^{-5} Wkg^{-1}
half-life	τ_j	4.47	0.704	14	1.25	Gyrs

Table A.1: Table of constant parameters. *oceanic basin surface area of Earth, **(Hirschmann et al., 2009; Crowley et al., 2011).

Mixing Time (Gyrs)	H_{sf}	
	constant mixing	variable mixing
0.4	1.711	1.722
0.6	1.715	1.706
0.8	1.708	1.724
1	1.737	1.724
1.5	1.760	1.724
2	1.704	1.724
2.5	1.667	1.737
3	1.602	1.741
3.5	1.475	1.752
4	1.281	1.763
4.5	1.202	1.782
5-9	1.706	1.796

Table A.2: H_{sf} values to constrain to 46 TW for $\eta(T, X)$ constant mixing and $\eta(T, X)$ variable mixing.

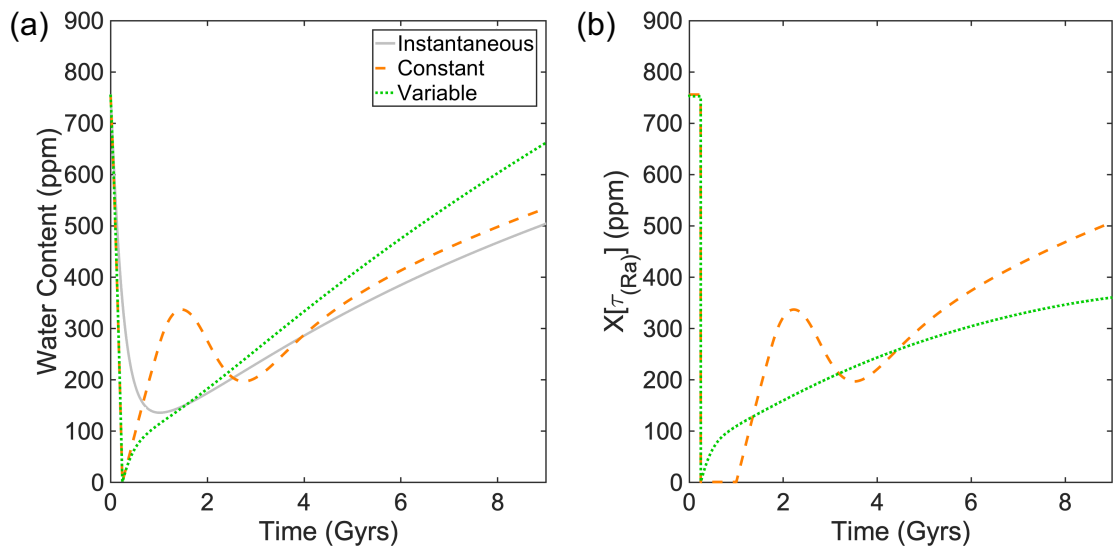


Figure A.1: The evolution of (a) mantle and (b) MOR water content for $\eta(T)$ with mixing. The evolution begins with the MOR processing hydrous material with 895ppm in the melt region i.e. the starting mantle water content. The high water content at the ridge promotes efficient degassing, such that the mantle is dried out rapidly. After this rapid degassing the system operates as explained in Section 3.1.

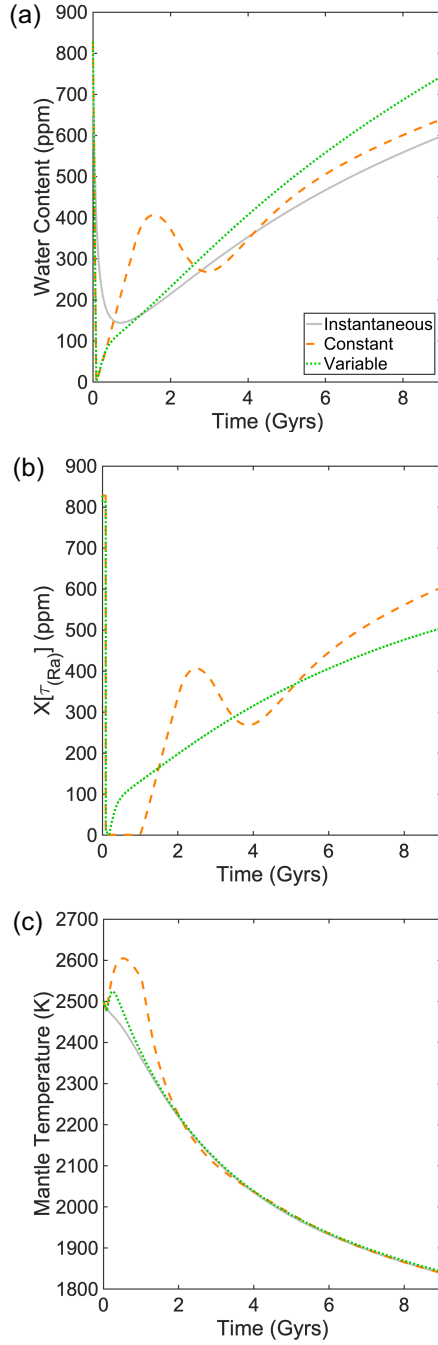


Figure A.2: The evolution of (a) mantle water content, (b) MOR water content and (c) average mantle temperature evolution for $\eta(T, X)$ with mixing. As in Figure A1, there is a period of rapid degassing before the evolution proceeds. With $\eta(T, X)$, there is also a feedback to the temperature evolution similar to results starting directly with a dry mantle.

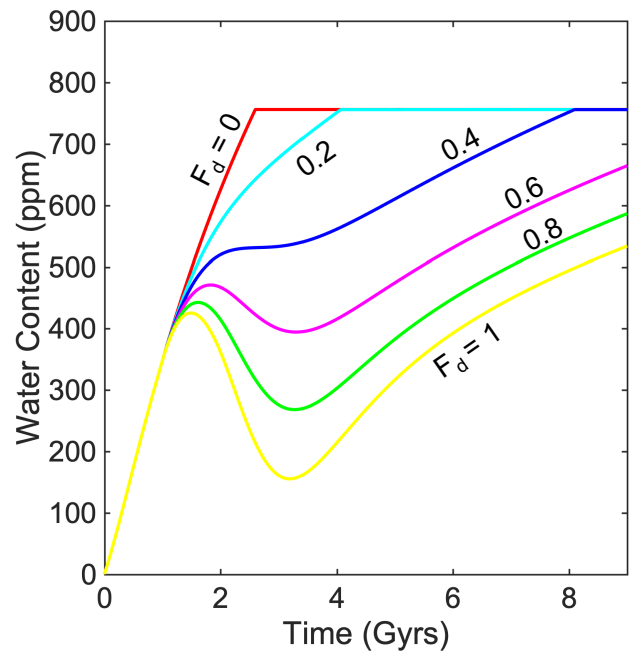


Figure A.3: Degassing efficiency also effects the net degassing period. As F_d decreases, the amplitude of net degassing reduces until $F_d < 0.4$, where net degassing no longer occurs, with timings changing little.