

21 **Abstract**

22 Ocean alkalinity enhancement (OAE) is a strategy for marine carbon dioxide removal that aims to increase the
23 total alkalinity (TA) of seawater to sequester atmospheric CO₂ in the form of dissolved inorganic carbon (DIC). An
24 intense alkalization of seawater resulting from OAE treatment could trigger a significant runaway carbonate
25 precipitation process, which may lead to a loss of initially added TA, thereby limiting its efficiency. Even under
26 natural background aragonite saturation states, a continuous yet barely detectable loss of TA is theoretically
27 expected to occur in seawater. With the additional increase through OAE, time ranges to initiate an appreciable
28 TA-loss process could be reduced significantly. Therefore, predicting the TA stability ranges might be a necessity
29 for application scenarios. The main drivers of the precipitation process are i) the aragonite saturation state of
30 seawater and ii) the available surface area for heterogeneous precipitation.

31 In this study, we refined the use of logistic functions to describe the temporal evolution of both drivers, with
32 experimental datasets using natural seawater from the Raunefjorden (Bergen, Norway; Temp.: ~11°C, Sal.:
33 ~32.6). The observed patterns were then used to derive a process-based model for calculating TA-loss rates,
34 focusing on the accelerated precipitation phase of the runaway process while considering saturation levels and
35 available particle surface area. The formation of carbonate phases reduces seawater TA concentrations, inducing
36 a delay or halting the TA-loss process. In addition, the sinking of precipitated particles decreases the potential
37 for further precipitation by reducing the available surface area in the system. To assess the impact of particle
38 sinking on TA-loss, their shape and size distribution were determined. Under the environmental conditions
39 presented here, TA-loss rates could be reduced by up to 30-40% due to the sinking of particles, after just one
40 day.

41 Integrating the proposed concepts into ocean models could enhance the accuracy of predictions regarding the
42 fate of added TA. Gaining insights into the evolution of the identified, seemingly stable TA levels can help prevent
43 accelerated precipitation phases. Additionally, an understanding of particle sinking or dilution processes,
44 reducing the available reactive particle surface area, is relevant to assess the efficacy and durability of OAE.

45

46 **1 Introduction**

47 To mitigate climate change and reach net-zero greenhouse gas emissions by the end of the century, negative
48 emission technologies (NETs) are necessary besides greenhouse gas emission reduction (UNFCCC, 2015)
49 considering the slow change in the development of the energy infrastructure, lifestyle of humanity, and national
50 goals for economic growth (Fuss et al., 2018; Iyer et al., 2015; Sers & Victor, 2018). Various carbon dioxide
51 removal (CDR) technologies have been proposed to help achieve the necessary negative emission trajectories
52 (Hartmann et al., 2013; IPCC, 2023; Minx et al., 2018; Rogelj et al., 2018). Among these, ocean alkalinity
53 enhancement (OAE) is a promising CDR method (Harvey, 2008; Ilyina et al., 2013; Khesghi, 1995; Rau & Caldeira,
54 1999), with the potential to geochemically sequester 3-30 Gt CO₂ yr⁻¹ (Oschlies et al., 2023; Renforth &
55 Henderson, 2017).

56 Enhancing total alkalinity (TA) could be achieved by two approaches: **1.** a non-CO₂-equilibrated (neq) or **2.** a CO₂-
57 equilibrated (eq) (Schulz et al., 2023). Through the neq approach, alkaline materials, such as silicate or hydroxide-
58 based mineral phases, could be introduced to seawater in the form of solids or solutions, allowing longer-term
59 CO₂ equilibration with the atmosphere through ingassing of atmospheric CO₂. In the eq approach, already
60 partially pre-CO₂-equilibrated solutions or carbonate-based substances could be released into seawater. Neq TA
61 addition strategies induce greater variations in the affected carbonate system, resulting in drastically reduced
62 *p*CO₂ and a rapid increase in pH values. While an eq TA addition results in less severe changes in ocean chemistry,
63 it is less efficient in generating carbon sequestration potential (Schulz et al., 2023; Suitner et al., 2024).

64 Depending on the introduced alkalinization method (see Eisaman et al., 2023) and the magnitude of treatment,
65 induced changes in the carbonate system could lead to adverse effects on biota (e.g. Faucher et al., 2025;
66 Ferderer et al., 2022; Gately et al., 2023; Goldenberg et al., 2024; Marín-Samper et al., 2024; Sánchez et al., 2024;
67 Xin et al., 2024) or in case of persistent oversaturation, result in the precipitation of secondary mineral phases
68 and therefore a loss of the introduced TA (Ilyina et al., 2013; Schulz et al., 2023). The process of TA leakage as a
69 consequence of OAE was recently described by several studies (see Fuhr et al., 2022; Hartmann et al., 2023;
70 Moras et al., 2022; Pan et al., 2021; Ringham et al., 2024; Suitner et al., 2024; Varliero et al., 2024). Within these
71 laboratory-based studies, self-sustaining runaway carbonate precipitation processes led to a significant decrease
72 in the added TA, which could even result in a net-loss of TA. TA stability ranges, and the evolution of the
73 precipitation process depend on the specific local environmental conditions such as temperature, salinity,
74 aragonite saturation state (Ω_{ar}), or suspended particle load of the treated water mass (Moras et al., 2024).

75 This study aims to demonstrate a general capability to predict and parametrize the temporal evolution of a
76 triggered runaway carbonate precipitation process during OAE approaches, using quantifiable and measurable
77 parameters. Stability ranges for the permanence of introduced TA additions were derived from these
78 parametrizations, enabling the prevention of secondary mineral formation and the optimization of future OAE
79 application scenarios.

80 Suitner et al. (2024) demonstrated the potential of inverse logistic functions to describe the temporal evolution
81 of TA loss during the runaway carbonate formation phase (see Fig. 1). Building on this concept, this study presents
82 a proof-of-concept mechanistic kinetic framework that combines empirically derived rate equations with

83 measurable parameters (such as carbonate saturation state and particle surface area) to reconstruct the
 84 temporal evolution of the TA loss and identify the main drivers of the process. The resulting parameterization is
 85 currently only calibrated to the experimental dataset and does not yet include additional environmental controls
 86 such as temperature, salinity, or suspended particles, but it provides a transferable calculation scheme that could
 87 later be implemented in predictive ocean models simulating OAE addition scenarios, as discussed by He & Tyka
 88 (2023), Ou et al. (2025), Schwinger et al. (2024), and Zhou et al. (2024).

89 The application of OAE may exceed critical levels for carbonate precipitation. For open ocean scenarios the rapid
 90 initiation of mixing processes would efficiently reduce the potential for secondary carbonate formation.
 91 Nevertheless, runaway carbonate formation may occur within enclosed geographic locations with physical
 92 features such as bays, estuaries, or lagoons. In addition, thermohaline layering (Bialik et al., 2022) or high
 93 sediment load (Wurgaft et al., 2016, 2021) might create conditions that lead to TA-loss processes.

94 To sustain a triggered runaway carbonate formation (Fig. 1), it is necessary to retain the precipitates in the
 95 system. Removal of these particles reduces the potential for continuous heterogeneous precipitation, thereby
 96 slowing down or halting the process. In this study, the empirically determined TA-loss rates were used to derive
 97 the quantity of precipitated particles. By identifying the particle sizes, shapes, densities, and sinking velocities,
 98 their potential residence times in the water column were estimated. Furthermore, we evaluated whether the
 99 formation of secondary minerals can supply sufficient surface area for a continuous detectable heterogeneous
 100 runaway process in an open-water body and whether the process would be interrupted or attenuated by
 101 removing particles due to their descent into deeper layers.

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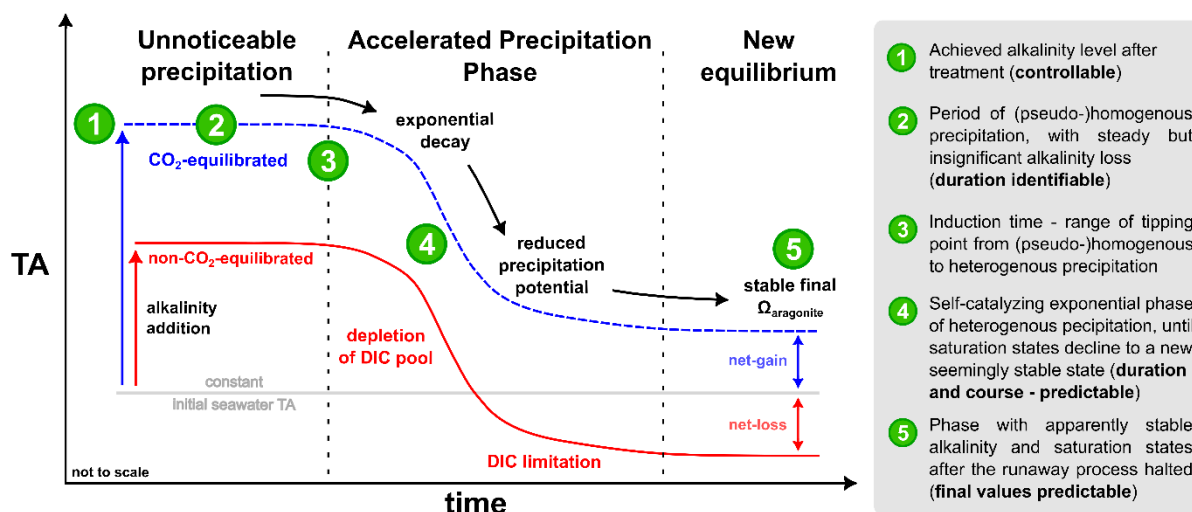


Figure 1: Modified conceptual scheme of a runaway carbonate precipitation process following liquid TA addition after Fig. 9 in Suitner et al., 2024 (not to scale).

103

104 2 Material and methods

105 2.1 Overview of experimental setups

106 All data analyzed in the present study derive from TA-gradient experiments described in Suitner et al. (2024).
107 During a field study from May to July 2022, natural seawater was collected at the Espeland marine station
108 (Raunefjorden, Bergen, Norway; 60.27° N, 5.20° E). Within 20-25 days lasting TA-gradient approaches, 250 ml
109 polystyrene cell culture bottles were filled with “filtered” (mesh size 0.2 μm) or “unfiltered” (mesh size 50 μm)
110 natural seawater ($\text{TA}_{\text{initial}} \sim 2190 \pm 10 \mu\text{mol kg}^{-1}$, $\text{DIC} \sim 1890 \pm 20 \mu\text{mol kg}^{-1}$, $\text{pH} \sim 8.25 \pm 0.05$, $\Omega_{\text{ar}} 2.8 \pm 0.4$ and Sal.
111 $\sim 32.6 \pm 0.1$) and incubated in a PMMA flow-through incubation box, mimicking the natural light and temperature
112 conditions (10-16°C). Each TA level was distributed among 3-4 bottles to allow sequential sampling while
113 minimizing head-space. TA was either increased with a 0.5 M NaOH (neq) or with a mix of 0.4 M
114 NaHCO_3 and 0.2 M Na_2CO_3 (eq) stock solutions to maintain ambient pCO_2 levels ($\sim 420 \mu\text{atm}$). TA, pH, salinity,
115 conductivity and temperature were measured using a Metrohm 888 Titrando (0.02 M HCl titration) and a WTW
116 MultiLine® multimeter. An overview of the experimental setup is given in Tab. 1; full methodological details are
117 provided in the supplementary information (SI).

118 The precipitated particles of three selected filters (0.2 μm PC), collected during incubation experiments within
119 previous campaigns published in Suitner et al. (2024) (neq ΔTA_{2600} and ΔTA_{2800} , Raunefjorden) and Hartmann et
120 al. (2023) (neq ΔTA_{2400} , Gran Canaria) were used to analyze particle sizes, morphology and their sinking velocities.
121 Similar to the Raunefjorden, the filters from the Gran Canaria experiment were obtained from a TA-gradient
122 experiment, conducted in local oligotrophic seawater ($\text{TA}_{\text{initial}} \sim 2411 \pm 5 \mu\text{mol kg}^{-1}$, $\text{DIC} \sim 2006 \pm 16 \mu\text{mol kg}^{-1}$, pH
123 $\sim 8.15 \pm 0.02$, $\Omega_{\text{ar}} 4.4 \pm 0.3$, $\text{Sal.} \sim 36.6$ Temp. ~ 23 °C), designed to assess the stability of alkalization approaches
124 (see SI for further details). Incubations during the Gran Canarian campaign ran for 4 days and followed the same
125 analytical protocol as the Norwegian series introduced above. A detailed description of the Gran Canaria setup
126 is provided in the SI.

127

Table 1: Overview of the experimental design of Raunefjorden precipitation experiments.

#	filter mesh size	CO ₂ state to atmosphere	Alkaline material	Runtime [days]	Range TA _{added} [$\mu\text{mol kg}^{-1}$]	TA _{added} gradient steps [$\mu\text{mol kg}^{-1}$]	Temperature [°C]
I	50 μm	non-equilibrated (neq)	NaOH	25	0-2800	200	10-11
II	0.2 μm				0-3400		11-13
III	0.2 μm	air-equilibrated (eq)	Na_2CO_3 / NaHCO_3	20	0-9200	800	12-16

128

129 **2.2 Curve fitting of the TA and Ω_{ar} evolution**

130 Building on Suitner et al. (2024), the numerical curve fit model used to describe the temporal development of TA
 131 and Ω_{ar} , was refined through the incorporation of observed TA-loss rates as an input factor, to provide continuous
 132 functions as a basis for further model calculations. The curve fit model utilized the consistent tendency of all
 133 observed runaway precipitation processes to follow inverse logistic trends in form of:

$$134 \quad f(t) = a e^{-b e^{-ct}} + d \quad (1)$$

135 for the temporal evolution of TA and Ω_{ar} . The coefficients **(d)** and **(a)** are defined by the achieved level of TA/ Ω_{ar}
 136 after the addition **(d)** and the final reached value after the runaway process halted **(a)**. Since these factors are
 137 predefined by the experimental setup, the curve fit model only numerically parameterizes the two coefficients
 138 **(b)** and **(c)**. Coefficient **(b)** represents the “induction time”, or the time required for CaCO_3 precipitation to
 139 become detectable in the TA measurements, depicted by the horizontal translation along the x-axis, while **(c)**
 140 denotes the timespan between start and end of an accelerated precipitation phase (APP). See Fig. 2 for a visual
 141 impression of the influence of iterations of each coefficient.

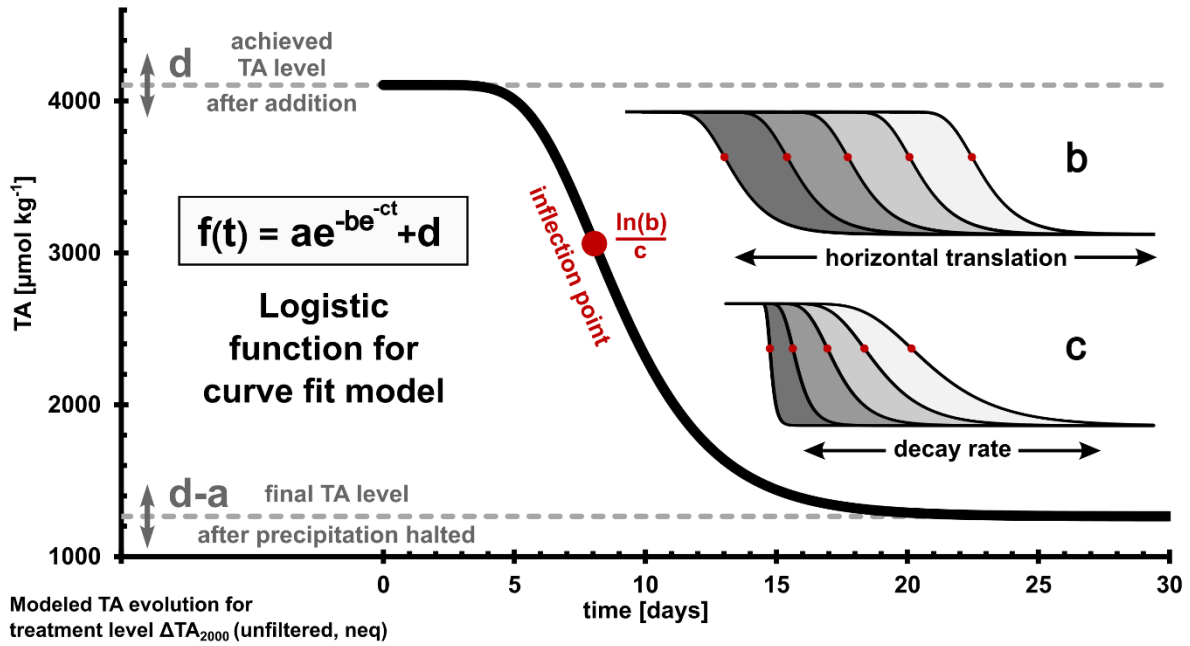


Figure 2: Overview and iterations of each coefficient **(a)-(d)** of the applied inverse logistic function for the numerical curve fitting; the inflection point is defined by $\ln(b)/c$; for further characteristics see Tjørve & Tjørve (2017).

142

143 **2.3 Empirical rate law and determination of loss rates**

144 A simple empirical rate law was used to evaluate the precipitation rates R [$\mu\text{mol m}^{-2} \text{h}^{-1}$] (see e.g., Inskeep &
 145 Bloom, 1985; Morse et al., 2007; Zhong & Mucci, 1989):

$$146 \quad R = k(\Omega_{ar} - 1)^n \quad (2)$$

147 The experimental precipitation rates were then fitted to the logarithmic form of Eq. (2) to determine the
 148 coefficients k (rate constant) and n (empirical reaction order):

$$149 \quad \log(R) = n(\Omega_{ar} - 1) + \log(k) \quad (3)$$

150 To correct for the variable surface area, r [$\mu\text{mol h}^{-1}$] was normalized for the assumed available active mineral
151 surface area (A in [m^2]) (adapted from Sjöberg, 1976).

$$152 \quad r = k A (\Omega_{ar} - 1)^n \quad (4)$$

153 As the gradient approaches could not provide a sufficient amount of precipitates to determine their surface area,
154 a one-week side experiment was conducted to estimate the mineral surface area generated during the runaway
155 precipitation process. By adding 3.8 mmol NaOH and 7.0 mmol NaHCO_3 to 40 L of 0.2 μm filtered natural
156 seawater (salinity 33) at 23°C, around 5 g of aragonite precipitates were generated to provide material for a BET
157 surface area measurement. Using N_2 adsorption (Brunauer et al., 1938), with a Quantachrome autosorb iQ at the
158 University of Hamburg, a surface area of $2.283 \pm 0.018 \text{ m}^2 \text{ g}^{-1}$ was determined. By the assumption that the surface
159 area is constant for all precipitates and that the entire lost TA is transformed into aragonite particles, the
160 experimentally determined TA-loss was used to calculate the surface area after each timestep, therefore allowing
161 to correct the precipitation rates.

162

163 **2.4 Particle analysis**

164 Three samples of precipitates, filtered through a 0.2 μm (PC) filter from the incubation experiments conducted
165 on Gran Canaria and in the Raunefjorden (see Section 2.1), were analyzed using a scanning electron microscope
166 (SEM; Hitachi TM4000 Plus Tabletop Microscope, University of Hamburg) to determine the morphology, size,
167 and relative abundance of the precipitated material. Length, width and shape of each particle were specified by
168 manual examination.

169 When sufficient precipitated material remained following SEM analysis, sinking velocities were determined from
170 the residual filter material using a FlowCam (Fluid Imaging Technologies Inc., Scarborough, United States). A
171 detailed description of the setup is provided in Suessle et al. (2023) and references therein.

172 **3 Results**

173 **3.1 Numerical logistic curve-fittings**

174 Three OAE gradient approaches by Suitner et al. (2024) were examined to test the stability of TA and to generate
 175 refined numerical logistic curve fittings of the temporal development of TA and Ω_{ar} (Figs. 3, S4 and S5). The
 176 coefficients **(b)** and **(c)** (see Fig. 2) were determined by numerical interpolation to optimize the fit to Eq. (1) and
 177 its derivative. Therefore, the shown functions were optimized to describe the temporal evolution, while also
 178 including the rate loss changes, which allowed an improved description of the runaway process in comparison to
 179 the approaches in previous studies. Outlying data points displaying an anomalous increase or stagnation in values
 180 in the filtered approaches were removed from curve-fitting calculations (for details see section 3.2 and SI). For
 181 each treatment, continuous differentiable functions to describe and analyze the runaway carbonate precipitation
 182 process during OAE approaches were generated. To illustrate the described processes and trends, the unfiltered
 183 neq approach was selected as an example (Fig. 3). The plots for the filtered approaches are provided in the SI
 184 (Figs. S4, S5 and S6).

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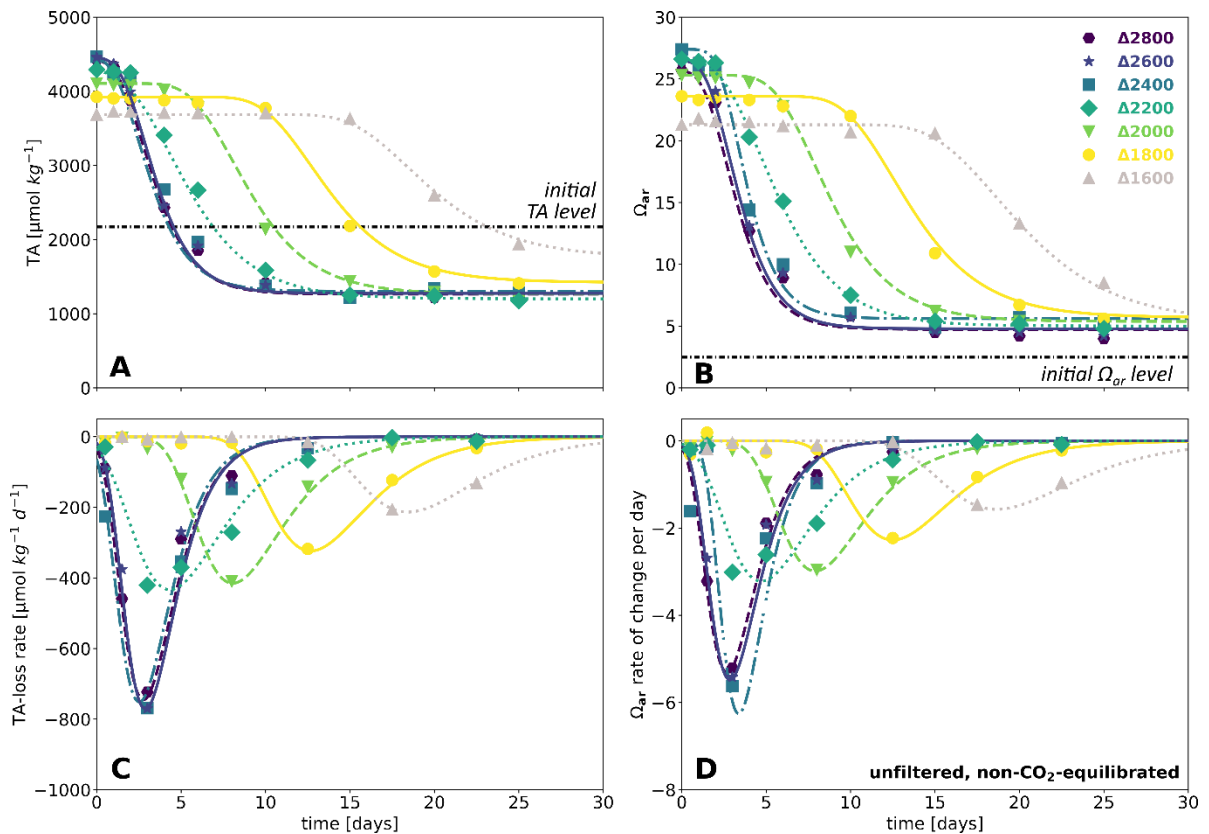


Figure 3: Results of the numerical curve fits – for the unfiltered neq approach, TA evolution over time (A), Ω_{ar} evolution over time (B), TA-loss rate over time (C), Ω_{ar} rate of change over time (D). Line plots: curve-fitted continuous functions, markers: measured data points, for related diagrams for filtered approaches see Figs. S4, S5 and S6.

186

187 For the unfiltered neq experiment (Fig. 3), treatment levels ΔTA_{1600} and higher entered into an APP after
 188 exceeding critical TA levels to initiate the runaway carbonate precipitation process. Treatments levels ΔTA_{2400} -

189 ²⁶⁰⁰ exhibited a buffering as a consequence of magnesium hydroxide precipitation (see Badjatya et al., 2022;
190 Ringham et al., 2024; Suitner et al., 2024; Varliero et al., 2024), which prevented an increase above $\sim 4470 \mu\text{mol}$
191 kg^{-1} in TA and ~ 27.4 in Ω_{ar} . The buffering effects were not recognized within the fitting procedure and the first
192 data point (after ~ 3 min runtime) of each treatment level was set as the baseline.

193 The continuous logistic curve-fits allow the estimation of the APP onset and duration. Parameter **(b)** correlates
194 with the induction time, while **(c)** correlates with the APP timespan (see Figs. 4 and 5). Under the present
195 conditions the regressions can be used as conversion equations for TA evolution. Related conversions and
196 regressions are provided in the SI (Fig. S7).

197

198 **3.2 Outliers**

199 In the experimental series performed in the Raunefjorden, a systematic cessation of the precipitation process
200 was observed in two of the three experimental setups. Precipitation arrested after 6 days, in the eq filtered
201 approach (Fig. S1) and after 8 days in the filtered neq approach (Fig. S2). For all TA treatments that had already
202 entered the accelerated precipitation phase, no further significant changes were detected in any measured
203 parameter.

204 Each TA treatment level was distributed to three individual bottles to minimize headspace effects while providing
205 sufficient volume for sampling. The bottles were sampled sequentially three to four times each, after which a
206 fresh set of bottles was opened. Although both affected series were run concurrently, a logistical offset of two
207 days separated their start times. All anomalies in the two independent series occurred between June 24th and
208 28th 2022, specifically in the second set of opened bottles, while the first and last sets of bottles displayed a
209 regular precipitation pattern. This temporal clustering suggests that an external factor, such as water
210 temperature, sunlight intensity, or a particular aspect of the sampling procedure, may have systematically
211 influenced the affected reactor bottles. Repeated measurements with calibrated standards ruled out an
212 analytical error, and the concurrent impact on both pH and TA confirms the reliability of the recorded values.
213 Consequently, the two sampling days that exhibited these anomalies were excluded from the curve-fitting
214 calculations. A comparison of the fits with and without these data points is shown in supplementary
215 Figures S1, S2, and S3.

216

217 **3.3 Induction time**

218 By employing the logistic curve fits, the temporal evolution of each approach could be parameterized. To identify
219 the temporal stability ranges and reflect the transition from stable to precipitation-dominated system modes, a
220 criterion of $40 \mu\text{mol kg}^{-1} \text{d}^{-1}$ rate of change in TA was set. This rate provides a sufficiently high threshold to exclude
221 a false detection due to natural variability or measurement errors, while still being low enough not to overlook
222 a significant fraction of TA-loss (see Fig. S15 for varying criteria).

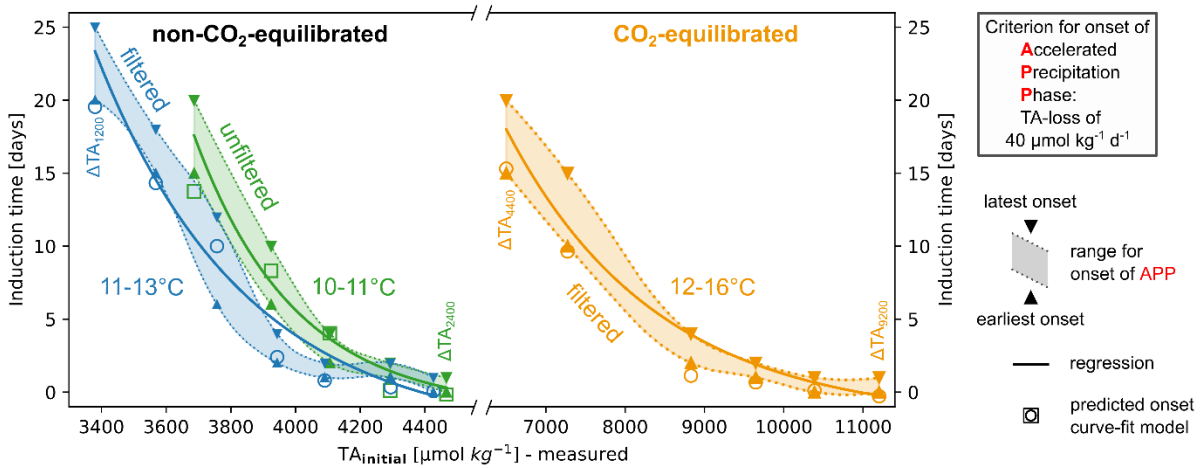
223 Based on this criterion, Fig. 4 illustrates the induction times for the APPs. The shaded ranges indicate
224 extrapolated timeframes between subsequent measurements during which the initiation of the APP for each
225 treatment was detected. The displayed regressions were calculated using the averaged times from two
226 consecutive measurement days. For comparison, hollow markers represent predictions from the presented

227 curve-fitted functions. The regressions of the induction times uniformly follow an inverse exponential trend of
 228 the type:

$$t(TA) = f e^{-g TA} - h \quad (5)$$

229 The employed data series covered a range of 25 days with progressively increasing induction times from 0 to 20
 230 days for treatments reaching ~ 4470 (ΔTA_{2400}) to $\sim 3380 \mu\text{mol kg}^{-1}$ (ΔTA_{1200}) in the filtered neq experiment and
 231 ~ 11200 (ΔTA_{9200}) to $\sim 6500 \mu\text{mol kg}^{-1}$ (ΔTA_{4400}) in the filtered eq experiment. Treatment levels above ΔTA_{2400} in
 232 the neq approaches exhibited an immediate onset of TA-loss due to the precipitation of secondary hydroxides
 233 and/or carbonate minerals, therefore, following the presented criterion, practically leading to their immediate
 234 entry into the APP process.

235 The same relationships and trends can also be applied using Ω_{ar} as a variable. While the neq approaches exhibited
 236 lower Ω_{ar} values (17.8-27.4) compared to the eq treatments (19.5-43.6), the onset of the APP in the neq
 237 experiments occurred significantly earlier. This indicates that Ω_{ar} is not the only decisive factor guiding the
 238 (pseudo-) homogeneous nucleation process, determining the induction time.



239 *Figure 4: Induction time for the onset of APP in relation to the initial TA addition level, based on the first detection of a TA-loss*
 240 *rate of $40 \mu\text{mol kg}^{-1} \text{d}^{-1}$. Each pair of triangle markers represents two consecutive measurement days during which the set loss*
 241 *rate criterion was met; hollow markers: predicted induction times for each treatment level, based on the introduced curve-fit*
 242 *model. Exponential regression of average experimentally detected induction time, see Eq. (5) in Tab. 2 for related functions.*

243
 244 *Table 2: Regressions of induction times, see Fig. 4. Note that the use of the given equation should not be generalized, as it is*
 245 *only valid under the presented environmental conditions. Also be aware that the resulting predictions of induction times far*
 246 *out of the specified TA addition ranges might not be accurate.*

$t(TA_{initial}) = f e^{-g TA_{initial}} - h \quad (5)$			Regression			
Treatment		Temp. [°C]	$f * 10^3$	$g * 10^{-4}$	h	R^2
non-equilibrated	unfiltered	10-11	2721.769	32.233	1.215	0.996
	filtered	11-13	39.633	21.646	2.972	0.977
equilibrated	filtered	12-16	0.603	5.243	1.934	0.988

247

248 **3.4 Timespan of the APP**

249 To describe the temporal evolution of TA and Ω_{ar} during the observed runaway processes for the present setups,
 250 coefficients **(a)** and **(d)** in Eq. (1) can be set, while **(b)** could be evaluated by empirical or modeled data.
 251 Consequently, only the duration of the APP represented by **(c)** needs to be estimated to enable the entire model
 252 description of the precipitation procedure. The discrete nature of sampling days with decreasing frequency of
 253 samplings towards the end of an experiment (up to 5 days) did not allow reliable empirical determinations of **(c)**.
 254 The displayed APP timespans in Fig. 5 were therefore determined by the predictions of the presented curve-fits
 255 (Fig. 3), based on the $40 \mu\text{mol kg}^{-1} \text{d}^{-1}$ TA-loss criterion to define the start and endpoint of the APPs. Fig. 5
 256 illustrates the related predicted timespans against the initially reached TA levels, categorized by the individual
 257 experimental setups. The neq APPs form distinct clusters for each approach, which again can be subdivided into
 258 treatments with and without the occurrence of immediate precipitation. Regardless of the initial TA
 259 enhancement level, treatments that exhibited an immediate decline due to $\text{Mg}(\text{OH})_2$ formation showcased
 260 almost identical APP spans (unfiltered ~ 8.8 and filtered ~ 5.9 - 7.4 days) within each approach. Although the neq
 261 treatments without $\text{Mg}(\text{OH})_2$ had the same starting conditions, the unfiltered experiments exhibited
 262 approximately 4 days longer APPs. In the eq approach, the APPs showed a continuous decrease as the initial TA
 263 addition levels increased, ranging from 5 to 11 days.

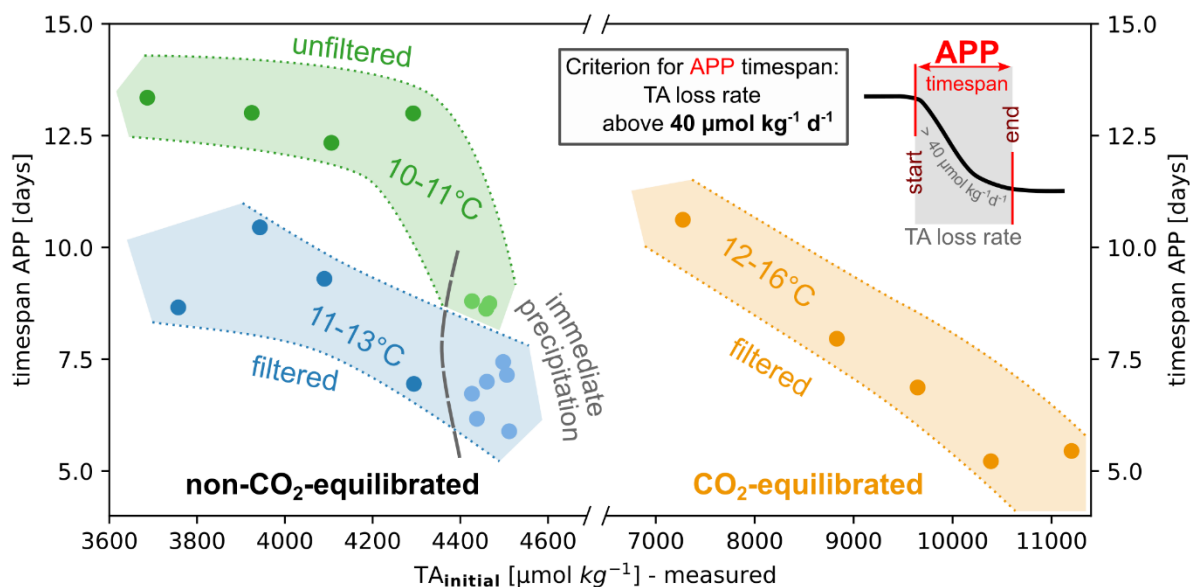


Figure 5: Overview timespans of APP in relation to the initial TA addition level; determined by the outcomes of the presented numerical logistic curve-fitting. Presented timespans are based on the introduced TA-loss criterion (see section 3.3), which was defined as period with rates above $40 \mu\text{mol kg}^{-1} \text{TA-loss d}^{-1}$; only treatments which reached the final stable stage were considered, neq treatments labeled with immediate precipitation showcased a loss of TA within the first 3 min of the experiment – most likely as a consequence of $\text{Mg}(\text{OH})_2$ formation.

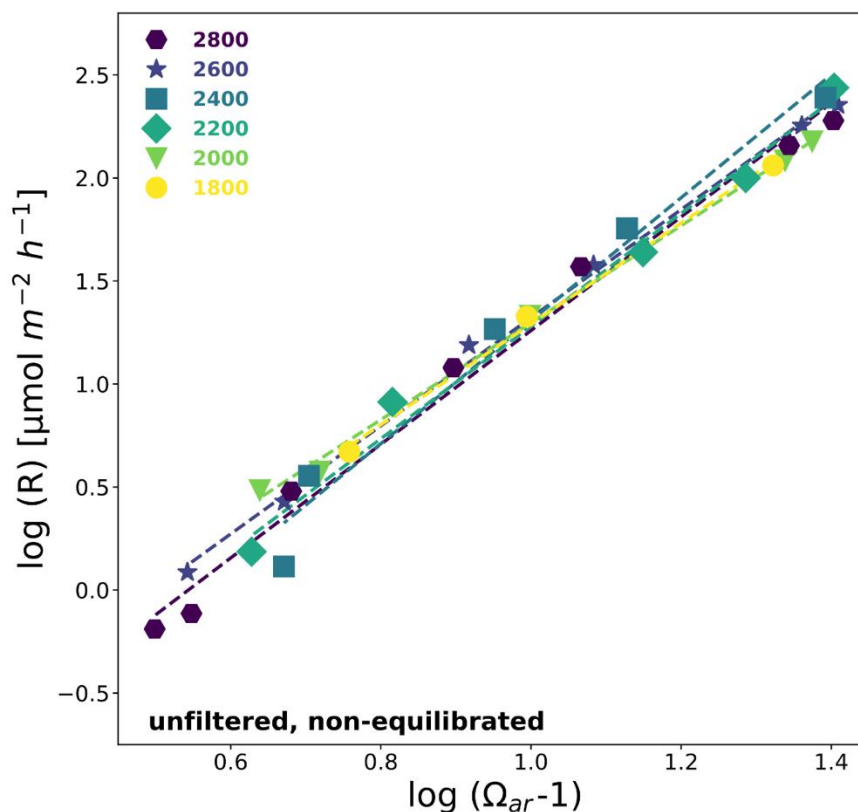
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266 3.5 Empirical rate equations

267 Additional insights into the reaction speed and the associated timespan of the APP can be obtained through
268 analysis of empirical rate law equations. As an example, Fig. 6 illustrates the relationship between the logarithm
269 of TA-loss rates normalized to the surface area and the aragonite saturation states for the unfiltered neq
270 approach (see Figs. S8 and S9 for details on the filtered approaches), focusing on treatments that entered the
271 APP. Throughout all experiments the logarithm of the surface area normalized precipitation rate R correlates
272 with the $\log(\Omega_{ar}-1)$, in accordance with similar observations reported in literature (e.g. Morse et al., 2007; Mucci
273 & Morse, 1983; Zhong & Mucci, 1989). The parameters n and k in Eq (2) were determined for each treatment
274 level in this work, as outlined in Eq (2) to (4) (section 2.3). Here, R represents the surface area normalized
275 precipitation rate, and k denotes the rate constant.

276 The values for n and $\log(k)$ derived from the linear regressions in the unfiltered neq treatments are provided in
277 Tab. 3 (see Tabs. S6 and S7 for filtered experiments). These values demonstrate reasonable consistency in n and
278 $\log(k)$ within each of the three separate experiments. Treatment levels influenced by the immediate formation
279 of $Mg(OH)_2$ as pH approached approximately 10.3 show minor deviations, the remaining treatment levels exhibit
280 reaction orders (n) within a relatively narrow range of 2.45 to 2.73. In comparison, $\log(k)$ values ranged between
281 0.30-1.68, showcasing a higher variability.



282 *Figure 6: Carbonate precipitation kinetics for unfiltered neq treatments that entered the APP; see Tab. 3 for related regressions*
283 *and rate equations.*

284 *Table 3: Overview of coefficients and regressions of empirical rate equations for unfiltered neq treatments, also see Fig. 6 and*
 285 *Tab. S8 for cross-comparison of all treatments.*

Treatment	$\log(R) = n(\Omega_{ar} - 1) + \log(k)$			
ΔTA	n	$\log(k)$	R^2	$\hat{\sigma}$
2800	2.76	-1.50	0.989	0.117
2600	2.62	-1.30	0.997	0.055
2400	2.98	-1.68	0.975	0.167
2200	2.73	-1.45	0.989	0.106
2000	2.35	-1.06	0.997	0.046
1800	2.45	-1.16	0.996	0.060
all	2.68	-1.39	0.985	0.106

286

287 **3.6 Evolution of particles and sinking speed**

288 To assess the impact of secondary precipitated particles during OAE approaches, precipitated materials from the
 289 studies by Hartmann et al. (2023) and Suitner et al. (2024) were analyzed for shape, size, and sinking velocity. As
 290 qualitatively depicted in these studies, the aragonite precipitates manifest and evolve in a variety of forms and
 291 sizes, ranging from stem-like structures, followed by double-broccoli shapes and ultimately forming closed
 292 spheres (see Fig. 7).

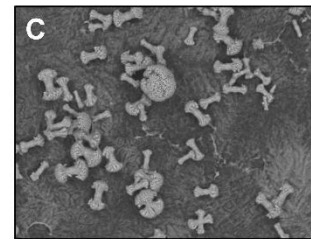
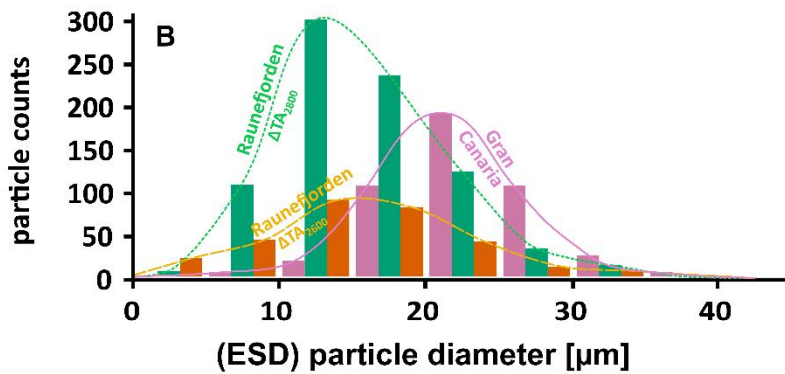
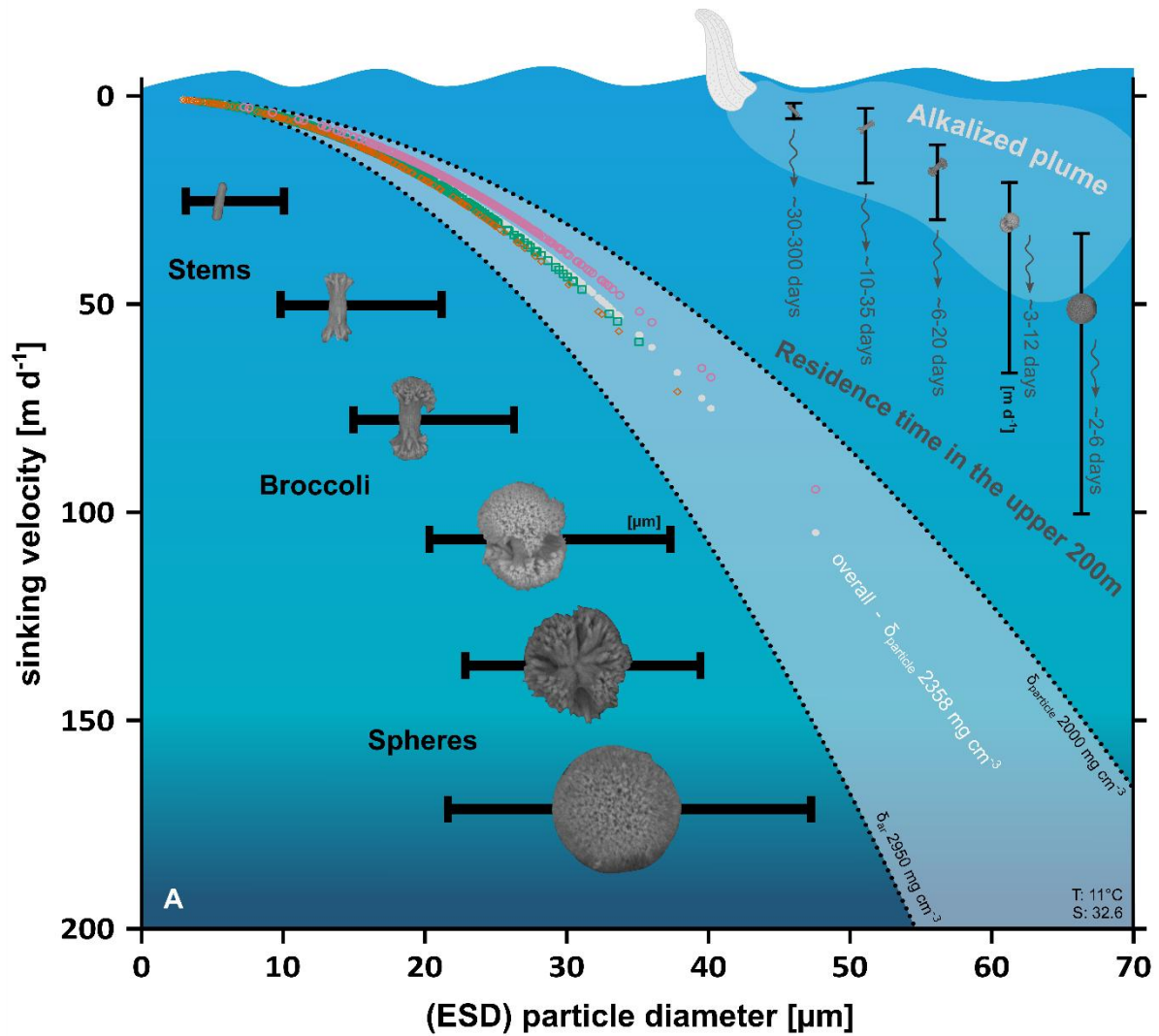
293 For this study the length and width distribution of 950 precipitated particles were determined by manual
 294 inspection of four overview SEM images (see Fig. S11) from Gran Canaria samples (see Hartmann et al., 2023 for
 295 details; analyzed treatment level: ΔTA_{2400} , filtered, neq, Temp. $\sim 23^\circ\text{C}$, Sal. ~ 36.5 , runtime 4 days) and the
 296 Raunefjorden, Bergen (this study and Suitner et al., 2024, see Figs. 3 and 7 therein; analyzed treatment levels:
 297 ΔTA_{2800} and ΔTA_{2600} , Temp. $\sim 11^\circ\text{C}$, Sal. 32.6, runtime 25 days – highest unfiltered neq treatments). Results of this
 298 evaluation are provided in Fig. S12. Length and width distributions of the formed particles follow distinct ratios,
 299 allowing the definition of three categories: **1.** Stems (<0.5), **2.** Broccoli ($0.5 < x < 0.9$) and **3.** Spheres (>0.9). Note
 300 that this method also categorizes regularly shaped, multi-branched particles as spheres (see Fig. 7). Precipitates
 301 from the Gran Canarian campaign primarily comprised well-developed broccoli and spherical-shaped particles,
 302 whereas the samples from the Raunefjorden were characterized by less evolved stems and broccoli as the
 303 dominant components. Although the runtime for the Gran Canarian sample was considerably shorter (4 days) in
 304 comparison to the Raunefjorden (25 days), the $\sim 12^\circ\text{C}$ difference in temperature led to significantly higher
 305 precipitation rates and more developed shapes. The analyzed Raunefjorden samples originate from the same
 306 experiment and differ only in the initially added TA-level of $200 \mu\text{mol kg}^{-1}$. Even this minor difference in TA
 307 addition resulted in the presence of more evolved shapes in the higher treatment.

308 The gravitational sinking velocities of precipitated particles were measured using a FlowCam setup (see Bach et
 309 al., 2012 for technical details). Based on the concept of equivalent spherical diameters (ESD) the density of each
 310 particle was calculated, revealing a range from 1.54 to 3.18 g cm^{-3} for ESD sizes between 12 and $50 \mu\text{m}$. The
 311 average density was determined to be 2.358 g cm^{-3} . The discrepancy with the density of aragonite ($\sim 2.95 \text{ g cm}^{-3}$)

312 may result from an overestimation of particle sizes in the calculation method, which relies on an inversion of
313 Stokes' Law for the terminal sinking velocity of perfect spheres. However, most particles are non-spherical and
314 contain numerous internal cavities within their structure (see Fig. S7), and their densities are therefore expected
315 to be lower than those of pure aragonite. The determined particle density was then used to calculate the
316 theoretical sinking velocities of the manually counted precipitated particles. To account for potential variability
317 in particle density, Fig. 7 presents a range of sinking velocities of the counted precipitates.

318 Measured sinking velocities for precipitated particles within the aforementioned density range varied from ~ 5 m
319 d^{-1} (14 μm particle) to ~ 47 m d^{-1} (41 μm particle). Recorded particles in the ESD range of 50-180 μm were not
320 included in the calculations, as they were not observed within the same filter material that was analyzed by visual
321 inspection. Discrepancies between measured and calculated values may reflect aggregation effects or technical
322 limitations of the utilized FlowCam to track particles smaller than 3 μm (Bach et al., 2012).

323 Derived from the calculated sinking velocities, the residence times within the upper 200 m of the water column
324 were determined. Accordingly, under idealized conditions, early precipitated stages, such as stems ($<10\mu m$),
325 could remain for a few months within the upper ocean layer, providing potential additional surfaces for an
326 ongoing heterogeneous precipitation if a continuous local alkalization is applied. In contrast, precipitates >30
327 μm would descend within days to deeper ocean layers, not affecting the precipitation behavior of continuous
328 surface alkalization attempts. Notice that sinking velocities are temperature and salinity dependent, and
329 therefore would vary under different environmental conditions (see Fig. S13).



Example SEM filter of carbonate precipitates and their variety of shapes (for further details see Fig. S11)

Figure 7: (A) Calculated sinking velocities of particles (hollow markers) as a function of ESD for each treatment (green squares: neq unfiltered ΔTA_{2800} – Raunefjorden, Bergen; orange diamonds: neq unfiltered ΔTA_{2600} Raunefjorden, Bergen; pink circles: neq filtered ΔTA_{2400} Gran Canaria). ESD distribution of stem, broccoli and sphere shaped precipitates (horizontal) and their calculated mean residence time in the mixed layer (assumed to be 200 m), while neglecting particle growth processes (B) related particles counts in size fractions of 5 μm , also see Fig. S12 for length:width distribution (C) example section of a SEM filter (ΔTA_{2600} Raunefjorden), see Fig. S11 for complete set of all filters.

331 **4 Discussion**

332 **4.1 General findings**

333 By analyzing the experimental datasets provided by Suitner et al. (2024), this study demonstrates that the
334 process of TA-loss during runaway carbonate precipitation follows quantifiable relationships. For the present
335 study, the compiled concepts allowed the description of the principles guiding the entire runaway process. The
336 obtained capability to predict TA-stability ranges, in terms of time and magnitude, might help prevent secondary
337 mineral formation, thereby optimizing the assessments for OAE application scenarios. Furthermore, the
338 simplicity of the logistic curve fit model, along with the demonstration that the carbonate precipitation follows
339 simple rate law equations (see Morse et al., 2007; Mucci & Morse, 1983; Zhong & Mucci, 1989), might facilitate
340 the straightforward integration of these fundamental mechanisms into ocean models like the studies by He &
341 Tyka (2023), Ou et al. (2025), Schwinger et al. (2024), Wang et al. (2022) or Zhou et al. (2024). The relationships
342 reported herein are specific to the experimental setup and the particular environmental conditions under which
343 they were measured. Consequently, projections or models that apply the presented precipitation patterns and
344 equations may not hold when conditions differ from those of the original study.

345

346 **4.2 Nucleation and onset of accelerated precipitation phase**

347 Previous studies examining the evolution of the runaway precipitation process in the context of OAE (Hartmann
348 et al., 2023; Moras et al., 2022, 2024; Suitner et al., 2024) observed and described considerable periods with
349 stable TA levels before the onset of the APP (see Fig. 1), depending on the TA and DIC levels.

350 In theory, even at natural background supersaturation levels in the ocean, (pseudo-)homogeneous precipitation
351 is expected to occur at very slow rates, on timescales of thousands of years (Pytkowicz, 1965, 1973). Regardless,
352 the nucleation and precipitation processes in ocean waters are suppressed by inhibitory species like Mg^{2+}
353 (Berner, 1975; Pan et al., 2021; Pokrovsky, 1998), phosphate- (Burton & Walter, 1990) or dissolved organic
354 matter (Chave & Suess, 1970; Kellock et al., 2022; Moras et al., 2024). Naturally occurring precipitation events in
355 the ocean are associated with sporadic occurrences such as flash floods (Wurgaft et al., 2016, 2021) or observed
356 during whiting events (Broecker & Takahashi, 1966; Bustos-Serrano et al., 2009; Morse et al., 2003), providing
357 high degrees of (re)suspended sediments that catalyze a heterogeneous carbonate precipitation procedure.

358 To consider the persistent (pseudo-)homogeneous precipitation within typical natural seawater supersaturation
359 ranges, the terminology concerning specific stability ranges of TA or timeframes for the onset of secondary
360 carbonate formation should be refined. However, within typical observation times in the Earth system, the
361 precipitation of secondary calcium carbonate in particle-free seawater solutions is expected to be suppressed to
362 Ω_{ar} values of approximately 11.3 or below (derived from Eq. (4) in Marion et al. (2009), based on data by Morse
363 & He (1993) and Morse et al. (2007)).

364 Nevertheless, even a $0.2\mu m$ -filtered natural seawater contains around $\sim 10^9$ particles per ml in the size range of
365 5-120 nm, already offering a total surface area of around $8 m^2$ per m^3 (cf. Wells & Goldberg, 1992), potentially
366 acting as a catalyst to initiate carbonate precipitation in alkalinity treated seawater. In the presence of surfaces

367 for pseudo-homogeneous/ heterogeneous precipitation such as suspended sediments, colloids, organic matter
368 or the introduced solid alkalization substrates, Moras et al. (2022) reported an Ω_{ar} threshold of ~5-7 for the
369 observable onset of carbonate formation for the given runtime of the experiment. Potentially, the colloidal
370 structure of $Mg(OH)_2$ precipitates (see Badjatya et al., 2022), typically formed above pH values of ~10.5 as a
371 consequence of TA addition (cf. Eisaman et al., 2023; Haas, 1916; Kapp, 1928; Suitner et al., 2024; Varliero et al.,
372 2024) could serve the same purpose and lower the threshold for carbonate precipitation. However, the
373 redissolution of the formed $Mg(OH)_2$ through the mixing and dilution processes, as described by Ringham et al.
374 (2024), may inhibit this effect and would also allow much higher short-term pH and TA concentrations around
375 an alkalinity injection site when using liquid stock solutions.

376 To characterize the transition from a state with negligible shifts in carbonate chemistry towards a phase primarily
377 driven by carbonate formation, a practicable criterion of a $40 \mu\text{mol kg}^{-1} \text{d}^{-1}$ TA-loss was set to determine the start
378 of the intensified precipitation stage (see Figs. 4 and 5). This criterion was also used to describe the induction
379 time, which is the period before a measurable onset of secondary carbonate formation can be detected (Fig. 4).
380 Since the induction time includes a fundamental uncertainty, it does not reflect an intrinsic property of the
381 treated solution itself and relies on the detection capability of the experimental setup (Söhnel & Mullin, 1988)
382 and might be chosen differently in future work (see Fig. S15 for varying criteria). While the selected criterion
383 already depicts relatively high loss rates, it enables detectable changes, distinguishable from measurement
384 uncertainties or natural variabilities. The overall emerging patterns related to the onset and duration of the APP
385 nevertheless remained relatively consistent across different tested threshold values.

386

387 **4.3 Predictability of the runaway process**

388 The consistent patterns during the TA-loss within all three experimental setups allowed the introduction of
389 continuous and differentiable functions for each treatment level, enabling further analysis to examine relevant
390 factors guiding the runaway process. Fuhr et al. (2022) utilized a comparable inverted logistic function to model
391 the process of secondary carbonate formation during olivine dissolution experiments in seawater. However, the
392 model was not consistently applied to describe a runaway carbonate precipitation process nor used as a general
393 predictive model to determine the stability ranges of the added TA in OAE approaches.

394 The characteristics of the logistic function applied in this study, facilitate the conversion of both empirically
395 determined and hypothetical parameters, such as induction time, duration of the APP (Fig. 5), or the initial and
396 final TA levels before and after the runaway process. The applicability of kinetic rate equations, combined with
397 the ability to quantify the precipitation process, enables a description and prediction of the temporal evolution
398 of the carbonate formation. This may facilitate the integration of the TA depletion procedure into various
399 predictive modeling approaches. Although these statements currently apply only under the tested
400 environmental conditions, they nonetheless suggest the general capability to assess a framework for guiding
401 time and TA level ranges in OAE approaches. Since the logistic model is based on experimental data from bottle
402 experiments, processes such as the removal of surface area due to the sinking of precipitated carbonate particles
403 were not accounted for. See section 4.6 for an approach to address this topic.

404 Under specified temperature and salinity conditions, as well as predefined TA/DIC levels after OAE treatment
405 and an estimated final Ω_{ar} after the precipitation process stopped (typically ~ 1.5 - 5.0 , see Fuhr et al., 2022;
406 Hartmann et al., 2023; Moras et al., 2022; Pan et al., 2021; Suitner et al., 2024), the resulting total TA-loss can be
407 computed. This calculation follows the condition that the TA-loss reflects the ideal 2:1 TA:DIC ratio during
408 carbonate mineral precipitation in seawater (Zeebe & Wolf-Gladrow, 2001). Given these assumptions, upper and
409 lower limits of the logistic function (coefficients **(a)** and **(d)**, Eq. (1)) can be determined. To characterize measures
410 such as induction time (coefficient **(b)**) and the duration of the APP (coefficient **(c)**), it is necessary to acquire
411 empirical data that account for the specific conditions of the deployment area. These data could either be
412 provided by actual experiments or model predictions, based on a comprehensive database which accounts for
413 broad ranges of TA, DIC, temperature, salinity, and practical available surface area, as well as inhibitory factors
414 or potential effects of biota. To validate the predicted precipitation behavior, additional gradient experiments
415 need to be conducted to better understand the geochemical reaction pathways.

416

417 **4.4 Empirical rate equations using Ω_{ar} and particle surface area during APP**

418 After passing the induction time to start the detectable carbonate formation process by (pseudo-/)/homogeneous
419 precipitation and overcoming the delaying inhibition effects (Marion et al., 2009; Morse & He, 1993; Schulz et
420 al., 2023), the triggered heterogeneous precipitation can be described by basic empirical rate equations (Fig. 6,
421 S8 and S9). These equations demonstrate the fundamental role of Ω_{ar} as a guiding factor for the precipitation
422 process. The kinetics of carbonate formation remained relatively consistent across all treatment levels within
423 each experimental approach (see Tabs. 3, S6 and S7). The observed consistent correlations between saturation
424 states and surface area normalized precipitation rates indicate that the runaway carbonate formation processes
425 during the present incubations followed the known kinetics of heterogeneous carbonate formation in seawater
426 (cf. Morse et al., 2007; Zhong & Mucci, 1989).

427 Fig. 8 illustrates the role of Ω_{ar} saturation states and generated particle surface area in guiding the TA-loss rates
428 during the precipitation process. The black line represents the curve fit of TA-loss rates of the unfiltered neq
429 ΔTA_{2000} approach; the experimentally determined rates are indicated by black triangles (also see Fig. 3c).
430 Assuming that the entire lost TA was transformed into aragonite precipitates with a surface area of $2.283 \text{ m}^2 \text{ g}^{-1}$
431 (see section 2.3), the total generated particle surface area (PSA) could be determined (red, dash-dotted line).
432 The overall expected TA-loss rate per m^2 (brown, dashed line) was obtained by utilizing the empirical logistic
433 curve fit for the temporal evolution of Ω_{ar} (Fig. 3b), normalizing it to 1 m^2 surface area, and inserting it into the
434 rate equation (Eq. (4)). Given that the system initially exhibits a negligible degree of PSA, the relatively high
435 precipitation potential by the Ω_{ar} saturation state does not result in a measurable TA-loss rate. Following the
436 presented concept, the consistently high Ω_{ar} values led to a continuous (pseudo-/)/homogeneous precipitation
437 during the induction time, thus causing a rise in PSA until the system shifts to heterogeneous precipitation, and
438 ultimately resulting in a detectable exponential runaway process. The interplay of precipitation potential by Ω_{ar}
439 and the practical available surface area could therefore be determined as the primary factors guiding the actual
440 observed TA-loss rates.

441 Within the uncertainties of the applied calculation steps and methods, the practical TA-loss rate could simply be
 442 described as the product of these two factors. To visualize this relationship, the dotted light blue line in Fig. 8
 443 represents an empirical rate law equation that combines the shown PSA (red, dash-dotted line) and the surface
 444 normalized expected precipitation rate (brown, dashed line) with the determined rate constant (k) and reaction
 445 order (n) for the ΔTA_{2000} treatment (see Tab. 3). The shape of the resulting function traces the measured TA-loss
 446 rates (black triangles) within reasonable accuracy (see Fig. S14 for other treatments). Be aware that any kind of
 447 inhibition effect is incorporated in the underlying experimentally determined temporal TA evolution, which
 448 represents the basis for all shown parameters.

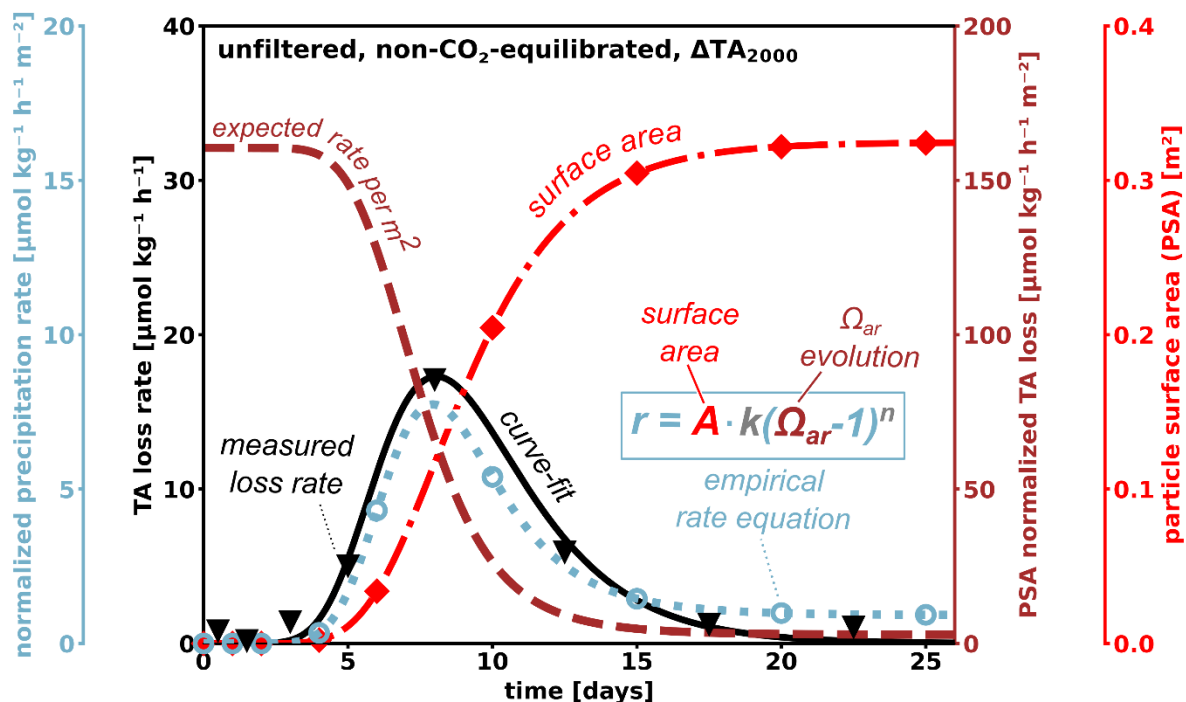


Figure 8: Conceptual figure, illustrating the interplay of Ω_{ar} and particle surface area guiding the TA-loss rate evolution (dashed, brown). After TA injection high Ω_{ar} values provide a high potential for the formation of carbonates by heterogeneous precipitation. In the absence of existing particle surface area (red dash-dotted), (pseudo-)homogenous precipitation would dominate the period until the start of the APP and the resulting runaway precipitation process. Observed TA-loss rates (black triangles) are therefore a combination of the available practical surface area and the precipitation potential by Ω_{ar} oversaturation. The related empirical rate equation (dotted, light blue) connects these two factors with the determined rate constant (k) and reaction order (n), tracing the shape and symmetry of the measured TA-loss rate. Hollow light-blue markers provide the output of the related empirical rate equations for each sampling day. While the potential to precipitate carbonates decreases with progressive precipitation, additional surface area is generated. Understanding how long particles remain in a critical zone to maintain a full-grown runaway process is therefore relevant for future considerations. The shown TA and loss rate data are taken from the empirical data sets for the neq unfiltered ΔTA_{2000} approach, see Fig. S14 for other treatments levels.

449

450 4.5 Could a runaway process be triggered in an open world context?

451 Mixing with untreated water around an injection point may lead to an efficient dilution below non-critical TA
 452 levels within seconds to minutes. Such a process would effectively prevent TA leakage, as described in this study,
 453 which assumes that the formed particles act as catalysts for future precipitation. This is supported by findings

454 from a mesocosm experiment and corresponding side experiments, in which the presence of additional
455 suspended aragonite particles accelerated TA-loss (Paul et al., 2024). In contrast, fresh seawater enhanced to the
456 same TA-levels did not show any TA-loss within 10 days in their experiments. These observations suggest that
457 free-floating particles in the water column can accelerate heterogeneous precipitation in a runaway style.
458 Precipitation events can be triggered naturally without additional treatment, especially for locations with already
459 relatively high Ω_{ar} background levels, for example, due to high evaporation rates (Bialik et al., 2022) or high
460 degrees of (re)suspended sediments present on carbonate platforms (Broecker & Takahashi, 1966; Bustos-
461 Serrano et al., 2009; Morse et al., 2003), or close to river mouths (Wurgaft et al., 2016, 2021) providing additional
462 PSA to catalyze precipitation events. Under inappropriate TA deployment circumstances, secondary mineral
463 formation might be triggered locally around injection sites, within short timescales. Moras et al. (2022) suggested
464 that visible APP starts around Ω_{ar} of 5. In the mostly particle-free waters of the Raunefjorden, this translates to
465 a ΔTA of $\sim 245 \mu\text{mol kg}^{-1}$ and $\sim 580 \mu\text{mol kg}^{-1}$ during neq and eq OAE approaches, respectively. The induction time
466 before the APP begins can be estimated using Eq (5), based on the specified TA-loss criterion of $40 \mu\text{mol kg}^{-1} \text{d}^{-1}$.
467 For the aforementioned equilibrium configurations, the projected induction times would be 1074 days and 143
468 days, respectively. However, the predicted induction times lie far outside the calibration ranges specified in this
469 study and may therefore be inaccurate. Since these projected APP induction times fall within the suggested
470 residence times of treated water in the upper ocean layers, it is necessary to conduct studies lasting at least as
471 long as the projected timespans, depending on local environmental conditions.
472 Significantly shorter induction times were identified for subtropical conditions (Temp. $\sim 23^\circ\text{C}$, Sal. ~ 36 psu, TA
473 $\sim 2400 \mu\text{mol kg}^{-1}$). Hartmann et al. (2023) described an onset of the precipitation after just 4 days for a $50 \mu\text{m}$
474 filtered neq incubation with initial values of $1050 \mu\text{mol kg}^{-1}$ for ΔTA and ~ 15 for Ω_{ar} . Within the same setting,
475 Paul et al. (2024) observed aragonite formation for a CO_2 equilibrated setup with $\Delta TA \sim 2300 \mu\text{mol kg}^{-1}$ and Ω_{ar}
476 9.74 ± 0.15 in mesocosms after 21 days.
477 The upper end members of TA perturbations examined in this study (neq: $\Delta TA > 2400 \mu\text{mol kg}^{-1}$; eq: $\Delta TA > 9000$
478 $\mu\text{mol kg}^{-1}$) are not intended to represent realistic target background values for permanent open-world scenarios,
479 as such values would need to remain biologically compatible over the long term. Rather, they represent short-
480 lived, near-field conditions that may occur close to an injection site or in enclosed environments where dilution
481 with untreated water is limited. The gradient approach used here therefore served as a controlled experimental
482 framework to investigate the principles of secondary carbonate formation under extreme conditions. Although
483 these small-scale incubations cannot fully reproduce natural systems, they provide a useful means to study the
484 underlying processes in a well-defined setting.

485

486 **4.6 Consequence of sinking particles removing surface area for carbonate formation**

487 Because the TA-loss rate is proportional to the surface area of particles (Eq. (4)), removal of particles due to
488 sinking processes or dilution with untreated water would result in slower precipitation rates. Small, formed
489 particles may remain in the upper layer for several months (Fig. 7), while medium-sized particles may leave the
490 treated water within a couple of days, depending on temperature and salinity conditions (Figs. 7 and S13).
491 Particles larger than $15 \mu\text{m}$ are expected to sink within one day under the environmental conditions of the

492 Raunefjorden. If those particles were removed by sinking while they were still growing, it can be estimated that
493 approximately 30-40% of the available surface area would be removed from the upper 10 m of the water column
494 within one day (also see SI). This would decrease the precipitation rate accordingly as surface area and formation
495 rates are linearly proportional. In a natural open ocean environment, the formation and sinking of precipitates
496 are likely to interact with the existing background of organic and inorganic particles. While any type of particles
497 could potentially serve as nucleation sites, aggregation would increase the sinking speed. These processes were
498 not included in the current model calculations but may be relevant under different conditions. In general, the
499 abundance and sinking of particles need to be addressed if the stability or loss of is to be assessed with a high
500 level of confidence.

501 Efficient dilution of the treated water parcels could therefore significantly reduce ongoing precipitation,
502 especially if the onset of the APP is initiated within the first few seconds. For example, this could be the case in
503 the wake of a ship, in OAE applications utilizing existing marine traffic to distribute TA throughout the world's
504 oceans (Caserini et al., 2021). Particle-based alkalization approaches would nevertheless temporarily introduce
505 additional surface area until its complete dissolution, and may cause the shift into the APP (Hartmann et al.,
506 2023).

507 **5 Conclusion**

508 TA leakage due to oversaturation sets a limit to the efficiency of OAE approaches. So far, the drivers of the
509 process could not be quantified, preventing the implementation of TA-loss terms in applicability assessments for
510 OAE. An induced runaway process follows predictable patterns that can be modeled using available surface area
511 and aragonite oversaturation, identified as the main factors for the given environmental settings.

512 However, it is expected that parameterizations will systematically change along temperature and salinity
513 gradients, as well as with naturally occurring variations in particle abundance and quality. The determination of
514 their impact was not within the scope of this work; instead, this study aimed to provide a framework for how
515 such needed parameterization can be achieved. Achieving a predictability of the induced TA-loss on a global scale
516 would allow the identification of suitable locations for OAE or optimizing applications. Therefore, further
517 research across salinity and temperature gradients would also enhance the predictive capabilities of ocean
518 models. Runaway TA-loss processes, as described in this study, would be significantly altered under natural
519 conditions by dilution and particle export processes. If sinking of particles and dilution with untreated water are
520 considered, the limitations of laboratory bottle experiments become evident. Nevertheless, they contribute
521 valuable parameterizations for model development. Field experiments are necessary to evaluate the validity of
522 the presented theoretical model framework with respect to dilution and particle sinking processes.

523

524 **Data availability**

525 Datasets have been made available via Zenodo: <https://doi.org/10.5281/zenodo.20324920>

526 **Author contributions**

527 The idea for this work was conceived by NS, with contributions by JH and SV. NS, SV and PS performed the surface
528 area- and sinking velocity/density measurements. NS interpreted the data with help from all co-authors. NS and
529 JH wrote the text with contributions from all co-authors.

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540 **Competing interests**

541 JHA is consulting the Planeteers GmbH. The contact authors have declared that all other authors have no
542 competing interests.

543 **References**

- 544
- 545 Bach, L. T., Riebesell, U., Sett, S., Febiri, S., Rzepka, P., & Schulz, K. G. (2012). An approach for particle sinking
- 546 velocity measurements in the 3–400 µm size range and considerations on the effect of temperature
- 547 on sinking rates. *Marine Biology*, 159(8), 1853–1864. <https://doi.org/10.1007/s00227-012-1945-2>
- 548 Badjatya, P., Akca, A. H., Fraga Alvarez, D. V., Chang, B., Ma, S., Pang, X., Wang, E., van Hinsberg, Q., Esposito,
- 549 D. V., & Kawashima, S. (2022). Carbon-negative cement manufacturing from seawater-derived
- 550 magnesium feedstocks. *Proc Natl Acad Sci U S A*, 119(34), e2114680119.
- 551 <https://doi.org/https://doi.org/10.1073/pnas.2114680119>
- 552 Berner, R. A. (1975). The role of magnesium in the crystal growth of calcite and aragonite from sea water.
- 553 *Geochimica et Cosmochimica Acta*, 39(4), 489–504. [https://doi.org/https://doi.org/10.1016/0016-](https://doi.org/https://doi.org/10.1016/0016-7037(75)90102-7)
- 554 [7037\(75\)90102-7](https://doi.org/https://doi.org/10.1016/0016-7037(75)90102-7)
- 555 Bialik, O. M., Sisma-Ventura, G., Vogt-Vincent, N., Silverman, J., & Katz, T. (2022). Role of oceanic abiotic
- 556 carbonate precipitation in future atmospheric CO₂ regulation. *Sci Rep*, 12(1), 15970.
- 557 <https://doi.org/https://doi.org/10.1038/s41598-022-20446-7>
- 558 Broecker, W. S., & Takahashi, T. (1966). Calcium carbonate precipitation on the Bahama Banks. *Journal of*
- 559 *Geophysical Research*, 71(6), 1575–1602. <https://doi.org/https://doi.org/10.1029/JZ071i006p01575>
- 560 Brunauer, S., Emmett, P. H., & Teller, E. (1938). Adsorption of gases in multimolecular layers. *Journal of the*
- 561 *American chemical society*, 60(2), 309–319.
- 562 Burton, E. A., & Walter, L. M. (1990). The role of pH in phosphate inhibition of calcite and aragonite
- 563 precipitation rates in seawater. *Geochimica et Cosmochimica Acta*, 54(3), 797–808.
- 564 [https://doi.org/https://doi.org/10.1016/0016-7037\(90\)90374-T](https://doi.org/https://doi.org/10.1016/0016-7037(90)90374-T)
- 565 Bustos-Serrano, H., Morse, J. W., & Millero, F. J. (2009). The formation of whittings on the Little Bahama Bank.
- 566 *Marine Chemistry*, 113(1-2), 1–8. <https://doi.org/https://doi.org/10.1016/j.marchem.2008.10.006>
- 567 Caserini, S., Pagano, D., Campo, F., Abbà, A., De Marco, S., Righi, D., Renforth, P., & Grosso, M. (2021). Potential
- 568 of Maritime Transport for Ocean Liming and Atmospheric CO₂ Removal. *Frontiers in Climate*, 3.
- 569 <https://doi.org/https://doi.org/10.3389/fclim.2021.575900>
- 570 Chave, K. E., & Suess, E. (1970). Calcium Carbonate Saturation in Seawater: Effects of Dissolved Organic Matter.
- 571 *Limnology and Oceanography*, 15(4), 633–637.
- 572 <https://doi.org/https://doi.org/10.4319/lo.1970.15.4.0633>
- 573 Eisaman, M., Geilert, S., Renforth, P., Bastianini, L., Campbell, J., Dale, A., Foteinis, S., Grasse, P., Hawrot, O., &
- 574 Löscher, C. (2023). Chapter 3: Assessing the technical aspects of OAE approaches. *State of the Planet*
- 575 *Discussions*, 2023, 1–52. <https://doi.org/https://doi.org/10.5194/sp-2-oae2023-3-2023>
- 576 Faucher, G., Haunost, M., Paul, A. J., Tietz, A. U. C., & Riebesell, U. (2025). Growth response of *Emiliania huxleyi*
- 577 to ocean alkalinity enhancement. *Biogeosciences*, 22(2), 405–415. [https://doi.org/10.5194/bg-22-405-](https://doi.org/10.5194/bg-22-405-2025)
- 578 [2025](https://doi.org/10.5194/bg-22-405-2025)
- 579 Ferderer, A., Chase, Z., Kennedy, F., Schulz, K. G., & Bach, L. T. (2022). Assessing the influence of ocean
- 580 alkalinity enhancement on a coastal phytoplankton community. *Biogeosciences*, 19(23), 5375–5399.
- 581 <https://doi.org/10.5194/bg-19-5375-2022>
- 582 Fuhr, M., Geilert, S., Schmidt, M., Liebetrau, V., Vogt, C., Ledwig, B., & Wallmann, K. (2022). Kinetics of Olivine
- 583 Weathering in Seawater: An Experimental Study. *Frontiers in Climate*, 4.
- 584 <https://doi.org/https://doi.org/10.3389/fclim.2022.831587>
- 585 Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W.,
- 586 Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., del
- 587 Mar Zamora Dominguez, M., & Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and
- 588 side effects. *Environmental Research Letters*, 13(6). <https://doi.org/10.1088/1748-9326/aabf9f>
- 589 Gately, J. A., Kim, S. M., Jin, B., Brzezinski, M. A., & Iglesias-Rodriguez, M. D. (2023). Coccolithophores and
- 590 diatoms resilient to ocean alkalinity enhancement: A glimpse of hope? *Science Advances*, 9(24),
- 591 eadg6066. <https://doi.org/10.1126/sciadv.adg6066>
- 592 Goldenberg, S. U., Riebesell, U., Brüggemann, D., Börner, G., Sswat, M., Folkvord, A., Couret, M., Spjelkavik, S.,
- 593 Sánchez, N., Jaspers, C., & Moyano, M. (2024). Early life stages of fish under ocean alkalinity
- 594 enhancement in coastal plankton communities. *Biogeosciences*, 21(20), 4521–4532.
- 595 <https://doi.org/10.5194/bg-21-4521-2024>

596 Haas, A. R. (1916). The Effect of the Addition of Alkali to Sea Water Upon the Hydrogen Ion Concentration.
597 *Journal of Biological Chemistry*, 26(2), 515–517. [https://doi.org/https://doi.org/10.1016/s0021-](https://doi.org/https://doi.org/10.1016/s0021-9258(18)87433-6)
598 [9258\(18\)87433-6](https://doi.org/https://doi.org/10.1016/s0021-9258(18)87433-6)

599 Hartmann, J., Suitner, N., Lim, C., Schneider, J., Marín-Samper, L., Arístegui, J., Renforth, P., Taucher, J., &
600 Riebesell, U. (2023). Stability of alkalinity in ocean alkalinity enhancement (OAE) approaches –
601 consequences for durability of CO₂ storage. *Biogeosciences*, 20(4), 781–802.
602 <https://doi.org/https://doi.org/10.5194/bg-20-781-2023>

603 Hartmann, J., West, A. J., Renforth, P., Köhler, P., De La Rocha, C. L., Wolf-Gladrow, D. A., Dürr, H. H., &
604 Scheffran, J. (2013). Enhanced chemical weathering as a geoengineering strategy to reduce
605 atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics*,
606 51(2), 113–149. <https://doi.org/https://doi.org/10.1002/rog.20004>

607 Harvey, L. D. D. (2008). Mitigating the atmospheric CO₂ increase and ocean acidification by adding limestone
608 powder to upwelling regions. *Journal of Geophysical Research: Oceans*, 113(C4).
609 <https://doi.org/10.1029/2007jc004373>

610 He, J., & Tyka, M. D. (2023). Limits and CO₂ equilibration of near-coast alkalinity enhancement. *Biogeosciences*,
611 20(1), 27–43. <https://doi.org/https://doi.org/10.5194/bg-20-27-2023>

612 Ilyina, T., Six, K. D., Segsneider, J., Maier-Reimer, E., Li, H., & Núñez-Riboni, I. (2013). Global ocean
613 biogeochemistry model HAMOCC: Model architecture and performance as component of the MPI-
614 Earth system model in different CMIP5 experimental realizations. *Journal of Advances in Modeling*
615 *Earth Systems*, 5(2), 287–315. <https://doi.org/https://doi.org/10.1029/2012ms000178>

616 Inskeep, W. P., & Bloom, P. R. (1985). An evaluation of rate equations for calcite precipitation kinetics at pCO₂
617 less than 0.01 atm and pH greater than 8. *Geochimica et Cosmochimica Acta*, 49(10), 2165–2180.
618 [https://doi.org/https://doi.org/10.1016/0016-7037\(85\)90074-2](https://doi.org/https://doi.org/10.1016/0016-7037(85)90074-2)

619 IPCC. (2023). Technical Summary. In *Climate Change 2021 – The Physical Science Basis* (pp. 35–144).
620 <https://doi.org/10.1017/9781009157896.002>

621 Iyer, G., Hultman, N., Eom, J., McJeon, H., Patel, P., & Clarke, L. (2015). Diffusion of low-carbon technologies
622 and the feasibility of long-term climate targets. *Technological Forecasting and Social Change*, 90, 103–
623 118. <https://doi.org/10.1016/j.techfore.2013.08.025>

624 Kapp, E. M. (1928). The precipitation of calcium and magnesium from sea water by sodium hydroxide. *The*
625 *Biological Bulletin*, 55(6), 453–458.

626 Kellock, C., Castillo Alvarez, M. C., Finch, A., Penkman, K., Kroger, R., Clog, M., & Allison, N. (2022). Optimising a
627 method for aragonite precipitation in simulated biogenic calcification media. *PLoS One*, 17(12),
628 e0278627. <https://doi.org/https://doi.org/10.1371/journal.pone.0278627>

629 Kheshti, H. S. (1995). Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy*, 20(9),
630 915–922. [https://doi.org/https://doi.org/10.1016/0360-5442\(95\)00035-F](https://doi.org/https://doi.org/10.1016/0360-5442(95)00035-F)

631 Marín-Samper, L., Arístegui, J., Hernández-Hernández, N., Ortiz, J., Archer, S. D., Ludwig, A., & Riebesell, U.
632 (2024). Assessing the impact of CO₂-equilibrated ocean alkalinity enhancement on microbial
633 metabolic rates in an oligotrophic system. *Biogeosciences*, 21(11), 2859–2876.
634 <https://doi.org/10.5194/bg-21-2859-2024>

635 Marion, G., Millero, F., & Feistel, R. (2009). Precipitation of solid phase calcium carbonates and their effect on
636 application of seawater S A–T–P models. *Ocean science*, 5(3), 285–291.
637 <https://doi.org/https://doi.org/10.5194/os-5-285-2009>

638 Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira
639 Garcia, W., Hartmann, J., Khanna, T., Lenzi, D., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente
640 Vicente, J. L., Wilcox, J., & del Mar Zamora Dominguez, M. (2018). Negative emissions—Part 1:
641 Research landscape and synthesis. *Environmental Research Letters*, 13(6).
642 <https://doi.org/10.1088/1748-9326/aabf9b>

643 Moras, C. A., Bach, L. T., Cyronak, T., Joannes-Boyau, R., & Schulz, K. G. (2022). Ocean alkalinity enhancement –
644 avoiding runaway CaCO₃ precipitation during quick and hydrated lime dissolution. *Biogeosciences*,
645 19(15), 3537–3557. <https://doi.org/https://doi.org/10.5194/bg-19-3537-2022>

646 Moras, C. A., Cyronak, T., Bach, L. T., Joannes-Boyau, R., & Schulz, K. G. (2024). Effects of grain size and
647 seawater salinity on magnesium hydroxide dissolution and secondary calcium carbonate precipitation
648 kinetics: implications for ocean alkalinity enhancement. *Biogeosciences*, 21(14), 3463–3475.
649 <https://doi.org/10.5194/bg-21-3463-2024>

650 Morse, J. W., Arvidson, R. S., & Lüttge, A. (2007). Calcium carbonate formation and dissolution. *Chemical*
651 *reviews*, 107(2), 342–381. <https://doi.org/https://doi.org/10.1021/cr050358j>

652 Morse, J. W., Gledhill, D. K., & Millero, F. J. (2003). CaCO₃ precipitation kinetics in waters from the great
653 Bahama bank. *Geochimica et Cosmochimica Acta*, 67(15), 2819–2826.
654 [https://doi.org/https://doi.org/10.1016/s0016-7037\(03\)00103-0](https://doi.org/https://doi.org/10.1016/s0016-7037(03)00103-0)

655 Morse, J. W., & He, S. (1993). Influences of T, S and PCO₂ on the pseudo-homogeneous precipitation of CaCO₃
656 from seawater: implications for whitening formation. *Marine Chemistry*, 41(4), 291–297.
657 [https://doi.org/https://doi.org/10.1016/0304-4203\(93\)90261-L](https://doi.org/https://doi.org/10.1016/0304-4203(93)90261-L)

658 Mucci, A., & Morse, J. W. (1983). The incorporation of Mg²⁺ and Sr²⁺ into calcite overgrowths: influences of
659 growth rate and solution composition. *Geochimica et Cosmochimica Acta*, 47(2), 217–233.
660 [https://doi.org/https://doi.org/10.1016/0016-7037\(83\)90135-7](https://doi.org/https://doi.org/10.1016/0016-7037(83)90135-7)

661 Oschlies, A., Bach, L. T., Rickaby, R. E. M., Satterfield, T., Webb, R., & Gattuso, J.-P. (2023). Climate targets,
662 carbon dioxide removal, and the potential role of ocean alkalinity enhancement. *State of the Planet*, 2-
663 oae2023, 1–9. <https://doi.org/10.5194/sp-2-oae2023-1-2023>

664 Ou, Y., Xue, Z. G., & Hu, X. (2025). A numerical assessment of ocean alkalinity enhancement efficiency on a
665 river-dominated continental shelf – a case study in the northern Gulf of Mexico. *Environmental*
666 *Research Letters*. <https://doi.org/10.1088/1748-9326/adaa8b>

667 Pan, Y., Li, Y., Ma, Q., He, H., Wang, S., Sun, Z., Cai, W.-J., Dong, B., Di, Y., Fu, W., & Chen, C.-T. A. (2021). The
668 role of Mg²⁺ in inhibiting CaCO₃ precipitation from seawater. *Marine Chemistry*, 237.
669 <https://doi.org/https://doi.org/10.1016/j.marchem.2021.104036>

670 Paul, A. J., Haunost, M., Goldenberg, S. U., Hartmann, J., Sanchez, N. S., Schneider, J., Suitner, N., & Riebesell, U.
671 (2024). Ocean alkalinity enhancement in an open ocean ecosystem: Biogeochemical responses and
672 carbon storage durability. *EGUsphere*. <https://doi.org/https://doi.org/10.5194/egusphere-2024-417>

673 Pokrovsky, O. S. (1998). Precipitation of calcium and magnesium carbonates from homogeneous
674 supersaturated solutions. *Journal of Crystal Growth*, 186(1-2), 233–239.
675 [https://doi.org/https://doi.org/10.1016/S0022-0248\(97\)00462-4](https://doi.org/https://doi.org/10.1016/S0022-0248(97)00462-4)

676 Pytkowicz, R. (1973). Calcium carbonate retention in supersaturated seawater. *American Journal of Science*,
677 273(6), 515–522. <https://doi.org/http://dx.doi.org/10.2475/ajs.273.6.515>

678 Pytkowicz, R. M. (1965). Rates of Inorganic Calcium Carbonate Nucleation. *The Journal of Geology*, 73(1), 196–
679 199. <https://doi.org/10.1086/627056>

680 Ramírez, L., Pozzo-Pirotta, L. J., Trebec, A., Manzanares-Vázquez, V., Díez, J. L., Arístegui, J., Riebesell, U.,
681 Archer, S. D., & Segovia, M. (2024). Ocean Alkalinity Enhancement (OAE) does not cause cellular stress
682 in a phytoplankton community of the sub-tropical Atlantic Ocean. *EGUsphere*, 2024, 1–34.
683 <https://doi.org/https://doi.org/10.5194/egusphere-2024-847>

684 Rau, G. H., & Caldeira, K. (1999). Enhanced carbonate dissolution as a means of sequestering carbon dioxide in
685 the ocean. *Energy Conversion and Management*, 40(17), 1803–1813. [https://doi.org/10.1016/S0196-8904\(99\)00071-0](https://doi.org/10.1016/S0196-8904(99)00071-0)

686

687 Renforth, P., & Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration. *Reviews of*
688 *Geophysics*, 55(3), 636–674. <https://doi.org/https://doi.org/10.1002/2016rg000533>

689 Ringham, M. C., Hirtle, N., Shaw, C., Lu, X., Herndon, J., Carter, B. R., & Eisaman, M. D. (2024). An assessment of
690 ocean alkalinity enhancement using aqueous hydroxides: kinetics, efficiency, and precipitation
691 thresholds. *Biogeosciences*, 21(15), 3551–3570. <https://doi.org/https://doi.org/10.5194/bg-21-3551-2024>

692

693 Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T.,
694 Marangoni, G., Krey, V., Kriegler, E., Riahi, K., van Vuuren, D. P., Doelman, J., Drouet, L., Edmonds, J.,
695 Fricko, O., Harmsen, M.,...Tavoni, M. (2018). Scenarios towards limiting global mean temperature
696 increase below 1.5 °C. *Nature Climate Change*, 8(4), 325–332. <https://doi.org/10.1038/s41558-018-0091-3>

697

698 Schulz, K. G., Bach, L. T., & Dickson, A. G. (2023). Seawater carbonate chemistry considerations for ocean
699 alkalinity enhancement research: theory, measurements, and calculations. *Guide to Best Practices in*
700 *Ocean Alkalinity Enhancement Research*, 2-oae2023, 2. <https://doi.org/10.5194/sp-2-oae2023-2-2023>

701 Schwinger, J., Bourgeois, T., & Rickels, W. (2024). On the emission-path dependency of the efficiency of ocean
702 alkalinity enhancement. *Environmental Research Letters*, 19(7). <https://doi.org/10.1088/1748-9326/ad5a27>

703

704 Sers, M. R., & Victor, P. A. (2018). The Energy-emissions Trap. *Ecological Economics*, 151, 10–21.
705 <https://doi.org/10.1016/j.ecolecon.2018.04.004>

706 Sjöberg, E. (1976). A fundamental equation for calcite dissolution kinetics. *Geochimica et Cosmochimica Acta*,
707 40(4), 441–447. [https://doi.org/https://doi.org/10.1016/0016-7037\(76\)90009-0](https://doi.org/https://doi.org/10.1016/0016-7037(76)90009-0)

708 Söhnle, O., & Mullin, J. W. (1988). Interpretation of crystallization induction periods. *Journal of colloid and*
709 *interface science*, 123(1), 43–50. [https://doi.org/https://doi.org/10.1016/0021-9797\(88\)90219-6](https://doi.org/https://doi.org/10.1016/0021-9797(88)90219-6)

710 Suessle, P., Taucher, J., Goldenberg, S., Baumann, M., Spilling, K., Noche-Ferreira, A., Vanharanta, M., &
711 Riebesell, U. (2023). Particle fluxes by subtropical pelagic communities under ocean alkalinity
712 enhancement. *EGUsphere*, 2023, 1–26. <https://doi.org/https://doi.org/10.5194/egusphere-2023-2800>
713 Suitner, N., Faucher, G., Lim, C., Schneider, J., Moras, C. A., Riebesell, U., & Hartmann, J. (2024). Ocean alkalinity
714 enhancement approaches and the predictability of runaway precipitation processes: results of an
715 experimental study to determine critical alkalinity ranges for safe and sustainable application
716 scenarios. *Biogeosciences*, 21(20), 4587–4604. <https://doi.org/10.5194/bg-21-4587-2024>
717 Suitner, N. (2026). Datasets for: Surface area and Ω -aragonite oversaturation as controls of the runaway
718 precipitation process in ocean alkalinity enhancement, Zenodo [data set]:
719 <https://doi.org/10.5281/zenodo.20324920>
720 Tjørve, K. M., & Tjørve, E. (2017). The use of Gompertz models in growth analyses, and new Gompertz-model
721 approach: An addition to the Unified-Richards family. *PLoS One*, 12(6), e0178691.
722 <https://doi.org/https://doi.org/10.1371/journal.pone.0178691>
723 UNFCCC. (2015). Report of the Conference of the Parties to the United Nations Framework Convention on
724 Climate Change (21st Session, 2015: Paris). Retrived December. Vol. 4. 2015.
725 Varliero, S., Buono, A., Caserini, S., Raos, G., & Macchi, P. (2024). Chemical Aspect of Ocean Liming for CO2
726 Removal: Dissolution Kinetics of Calcium Hydroxide in Seawater. *ACS Engineering Au*.
727 <https://doi.org/https://doi.org/10.1021/acsengineeringau.4c00008>
728 Wang, H., Pilcher, D. J., Kearney, K. A., Cross, J. N., Shugart, O. M., Eisaman, M. D., & Carter, B. R. (2023).
729 Simulated impact of ocean alkalinity enhancement on atmospheric CO2 removal in the Bering Sea.
730 *Earth's Future*, 11(1). [https://doi.org/ https://doi.org/10.1029/2022EF002816](https://doi.org/https://doi.org/10.1029/2022EF002816)
731 Wells, M. L., & Goldberg, E. D. (1992). Marine submicron particles. *Marine Chemistry*, 40(1-2), 5–18.
732 [https://doi.org/https://doi.org/10.1016/0304-4203\(92\)90045-C](https://doi.org/https://doi.org/10.1016/0304-4203(92)90045-C)
733 Wurgaft, E., Steiner, Z., Luz, B., & Lazar, B. (2016). Evidence for inorganic precipitation of CaCO3 on suspended
734 solids in the open water of the Red Sea. *Marine Chemistry*, 186, 145–155.
735 <https://doi.org/https://doi.org/10.1016/j.marchem.2016.09.006>
736 Wurgaft, E., Wang, Z. A., Churchill, J. H., Dellapenna, T., Song, S., Du, J., Ringham, M. C., Rivlin, T., & Lazar, B.
737 (2021). Particle Triggered Reactions as an Important Mechanism of Alkalinity and Inorganic Carbon
738 Removal in River Plumes. *Geophysical Research Letters*, 48(11), 277.
739 <https://doi.org/https://doi.org/10.1029/2021gl093178>
740 Xin, X., Goldenberg, S. U., Taucher, J., Stuhr, A., Aristegui, J., & Riebesell, U. (2024). Resilience of Phytoplankton
741 and Microzooplankton Communities under Ocean Alkalinity Enhancement in the Oligotrophic Ocean.
742 *Environ Sci Technol*. <https://doi.org/10.1021/acs.est.4c09838>
743 Zeebe, R., & Wolf-Gladrow, D. (2001). *CO2 in Seawater: Equilibrium, Kinetics, Isotopes*. Elsevier Oceanography
744 Book Series. 65.
745 Zhong, S., & Mucci, A. (1989). Calcite and aragonite precipitation from seawater solutions of various salinities:
746 Precipitation rates and overgrowth compositions. *Chemical geology*, 78(3-4), 283–299.
747 [https://doi.org/https://doi.org/10.1016/0009-2541\(89\)90064-8](https://doi.org/https://doi.org/10.1016/0009-2541(89)90064-8)
748 Zhou, M., Tyka, M. D., Ho, D. T., Yankovsky, E., Bachman, S., Nicholas, T., Karspeck, A. R., & Long, M. C. (2024).
749 Mapping the global variation in the efficiency of ocean alkalinity enhancement for carbon dioxide
750 removal. *Nature Climate Change*, 1–7. <https://doi.org/https://doi.org/10.1038/s41558-024-02179-9>

751